A WATER RESOURCE MANAGEMENT AND PLANNING DECISION SUPPORT SYSTEM FOR THE SULTANATE OF OMAN

By

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وجعلنا من الماء كل شيء حي

We Made From Water Every Living Thing

(The Holy Qur'an XXI, Verse 30)

Dedicated to my wife Salma
my daughters Laila & Nashwa
and my son Mohammed

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A WATER RESOURCES MANAGEMENT AND PLANNING DECISION SUPPORT SYSTEM FOR THE SULTANATE OF OMAN

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A water resources management and planning decision support system (DSS) was designed for a specific study area in the Sultanate of Oman. The purpose was to demonstrate how the use of the decision support system could result in formulation and implementation of rational water resources management and planning policies in the Sultanate of Oman. The DSS architecture was comprised of four major components. A database (dbase IV), geographic information system (GIS) using ArcInfo, satellite image processing GIS using the Earth Resources Data Analysis System (ERDAS) and a multi criteria decision making model, MATS (Multi Attribute Tradeoff System), were employed to synthesize the data and evaluate the final policy alternatives. The results demonstrated that a DSS can

provide valuable support to the water resources manager and the impact of graphics output on the visualization of spatial and temporal water resources data. The DSS also illustrated the value of databases that can store and organize water resources related data in a format that provides the support for rational multiattribute decision making.

CHAPTER I

INTRODUCTION

Lesser developed countries (LDCs), particularly those in the Arabian Gulf, are experiencing rapid development. Ambitious infrastructure projects have been implemented in the past two decades which have resulted in the formation of impressive urban centers and communication networks. In the course of rapid development these nations have depended on international consultants and engineering firms to provide water solutions that were quick but not necessarily sound in the long run. As a legacy to past decision makers, some of the worlds largest and most sophisticated desalination plants have been developed in order to support this development. The current challenge to decision makers in this region is how they can maintain and support continued development and achieve the economic diversity that will release them from becoming hostage to a finite and scarce resource.

The Sultanate of Oman has been facing this challenge. With a rapidly growing population, its leaders have moved toward facilitating economic diversity and agricultural self sufficiency. The result is that Oman has reached a point in development whereby the greatest constraint to

sustainable development is the availability and protection of the Nation's finite water resources.

Statement of the Problem

Water is a major constraint in the development of any nation, Oman not being the exception. The scarcity of natural sources of usable water may represent the greatest constraints to evolving a modern, but yet sustainable, economy in Oman and other nations of the Arabian Gulf region. Both intensive and geographically expanded agricultural development has been impeded by limited water supplies, as is industrial expansion. Potable supplies for urban areas in Oman have also limited development.

The water resource problems of Oman are complex, and solutions are not readily identifiable. The mentality and attitudes of the people are clouded by the illusion that water is in plentiful supply and the trend of government projects in Oman seem to perpetuate this form of thinking. In many respects the fortunes of the oil revenues earned by the country in the last decade have served to condition planners to believe that solutions to the nation's water needs can be solved given sufficient financial resources.

Technical solutions to water resources problems developed in the western countries can be adapted to try and solve some of the problems, however management policies that may be adopted in the west are not so readily accepted in Oman. This does not imply that

solutions cannot be developed for Oman's water resources problems.

Governmental policies concerning water resources have thus far been designed to meet the ever increasing demand. High revenue from oil exports have enabled the government to service the water demands of the nation by expanding desalination plant capacity, as well as drilling and exploring deeper aquifers. The advent of the oil price crash of the mid-80's caused the government of Oman to realize that sustainable development cannot be supported by oil revenues alone.

As a result of lower oil prices the government has made great efforts to encourage the development of other industries to reduce Oman's dependence on oil revenues. The future development of these industries and the maintenance of the ever expanding infrastructure, however, are heavily dependent on water resources development. The dependency on water suggests the need for a comprehensive strategy for sound water resources development of the nation. Coordinated efforts in the evaluation of alternative sources of water are a first step towards meeting these goals. Implementation of both coordinated and feasible water policies is critical to the overall viable development of the nation's economy.

Oman has reached a point in its development whereby a realistic and objective evaluation of the water resources management and planning activities of each government

agency must be assessed according to the long term feasibility and impact of the activity towards sustainable development of the country. A rational method to quantify and analyze the water resources and related activities of the nation to support the implementation of sound and effective water resources management and planning policies is urgently needed. To date such a method has not evolved in Oman.

One reason is the rapid change in the institutional setting in Oman. The traditional water laws which were governed by fundamental Islamic water rights have been changed. Historically, these laws declared water as "mubah" or free for all (to satisfy thirst) and were associated with communal appropriation of water according to the needs of the community. Each community provided for itself. With modern water laws, the government has declared all water to be a National resource and as such empowers the relevant governmental agencies to develop (and protect) the Nation's water resources according to laws declared by Royal Decree.

The result of the new water institutions has been a need for more coordination of policies between the various governmental agencies concerned with water resources management. Each agency currently designs and implements policies aimed at achieving each agency's development goals. Some duplication of effort has occurred.

Most efforts have involved building structures. Further structural solutions, for example, construction of large desalination plants, may not be justifiable even though greater economies of scale could be realized. A realistic evaluation of the Nation's development goals within the constraints of limited water resources is needed in order to direct future policies.

Until recently the primary objective of water resources managers and planners has been to meet the ever increasing demand for water. The philosophy of supply management continues to dominate water management policies in the Arabian Gulf nations (Akkad, 1989). The dynamics of water politics makes water management and policy making a multi-disciplinary process that requires input and collaboration from engineers, social scientist and managers.

Globally the threat of decreasing water supplies are causing some decision makers to speculate that perhaps the scarcity of water in specific regions of the world, particularly in the middle east, could pose the greatest threat to world peace (Tolba, 1988). Decision makers in Washington are calculating strategies for protecting the critical water supply of the Arabian Gulf countries (Starr, 1991). The stability of developing nations is a concern to both the developed nations and the individual sovereign states.

The complex political motives behind Operation Desert Storm are overshadowed by the reality that instability in these remote desert nations is a direct threat to the existence and well being of the economically developed nations. The viability of the economies of the developed nations hinges on the uninterrupted flow of crude oil from this region. Global economics and politics have evolved into a complex network of critical interdependencies; the network of trade and economic pacts have reduced the world into a dynamic milieu of codependencies. The water security of developing countries is clearly a political as well as technological challenge to the rest of the world (Starr, 1991).

Purpose of the Study

The purpose of this study is to design a decision support system that would demonstrate how water resources management and planning policies can be evaluated, implemented and supported. With such a decision support system, decision makers can better evaluate the many variables that can impact water resources development.

Effective water resources development policies most often address multiple objectives e.g., land use, hydrogeological characteristics, well inventories, well characteristics and water use. All are critical attributes of the multiobjective function that must be evaluated by decision makers to assess the impacts of

specific water resource policies. The decision support system designed in this study concentrates on synthesizing the relevant information related to the multiobjectives for water development through and utilization of appropriate supporting software packages. Use of the system will result in improved water resources management policies.

Organization of the Study

The present chapter has reported the purpose of the study and the problem being addressed.

Chapter II discusses the pertinent literature for the five primary components associated with rational water resources planning and management.

Chapter III describes the background and the institutional framework of water supply production, management and planning in the Sultanate of Oman.

Chapter IV defines the hydrogeologic characteristic of the study area.

Chapter V presents the methods and materials utilized to conduct the study.

Chapter VI presents the results of the study.

Chapter VII discusses the results and offers conclusions.

CHAPTER II

WATER RESOURCES MANAGEMENT IN PERSPECTIVE

Water experts are continuously proposing innovative and dynamic solutions to address the water problems of the middle eastern region (Munasinghe, 1991; Shahin, 1989; Starr, 1991). As suggested by Al-Rawahy and Smith (1991a), however, solutions to the region's water resources problems must ultimately be formulated by the users who most fully understand the complexities of the Arab society and historical significance of water resources of the region. This recommendation is supported by many experienced international water consultants who have noted that "wholesale transfer of U.S. law, design, and attitude is hazardous" (Wolman, 1989; Fairchild, 1986).

The lack of indigenous qualified technical cadre in the Arabian Gulf nations (Hamdan, 1989), however, necessitates the adoption of foreign designs and technology to solve the immediate water supply problems. Many of the tools used in the decision making process are not necessarily sensitive to cultural constraints. The basic principles that must be followed to formulate rational water management and planning policies are

universal. How they are adapted to solve the problems of a specific region remains at the discretion of the decision maker.

Any good decision making requires good information (Viessman, 1989), consequently the organization and manipulation of this information to achieve the desired results is the responsibility of the decision maker. Critical to any decision making process is the availability of relevant information; decision makers must often process that information through various means of re-expression in order to use the information more efficiently (Hopple, 1988). The availability of information is not a panacea to formulating policies or making decisions; on the contrary, it can be argued that too much information can be decidedly dysfunctional (Taylor, 1986). The challenge for decision makers is to develop tools and mechanisms that help users make sense of the vast array of information (Hopple, 1988). Developing tools that will facilitate rational decision making is the challenge of the innovative water resources planner.

Components of Water Resources Management and Planning

The components of a rational water supply and management plan that are being proposed in this study must be considered in the context of a developing country's needs and objectives. In such a setting, water resources management plans should be designed to be dynamic. Plans

need to be adaptable to the rapidly changing needs of the developing society.

The ultimate goal of such a dynamic plan is to improve decisions as conditions dictate. As such, the following components can be viewed collectively as a functional decision support system useful over time. The essential components to effective water resources management planning in a region are described as:

- Data organization and storage
- Spatial data
- Hydrologic models
- Institutional framework
- Decision making capabilities

Database Management Systems for Data Organization and Storage

The collective work of Dulaney and Rowe (1991), offers comprehensive guidance to designing a ground water database that can be used as an effective tool in ground water management.

In addressing the problem of diminishing ground water resources of Nassau County, New York, Maimone (1989) reports that one of the most important means of formulating a ground water management program is by implementing a data system that can facilitate the problem analysis, the monitoring of results, and the design of alternative solutions to the problem. In this case a database was designed to store the relevant data using the

dBase III Plus relational database software. Relational databases offer a powerful means of linking data files by means of a common attribute (entity), which in this case was a well number. Microsoft Chart was used as the main graphics package for reports. To facilitate the expression of spatial data a contouring package, Surfer from Golden Software, was used. Water level and water quality contours were drawn by transferring data directly from data files. Although the ultimate use of the system has yet to be defined, it does serve to demonstrate how an effective computerized data system can be developed to support a comprehensive ground water management program.

Other examples of the effectiveness of a ground water database in water resources management and planning include well permitting, salt water pollution, and landfill site location (Dulaney and Rowe, 1991). Briz-Kishore (1989) rationalizes that the planning, allocation and utilization of water resources depend on the socioeconomic development schemes of the society which can be integrated with a comprehensive geohydrological database to formulate sound water management decisions.

The need to optimize operations has forced many organizations to implement computerized data storage and retrieval systems in conjunction with other computer software (Mancinelli, 1986). By taking a systems approach to database design, Chow et al., (1986) were able to propose a comprehensive computer aided water resources

planning model which integrated the database with graphics and plotting software. The central element of the planning process was the organization of data in a retrieval format. Specialized software is being designed by some workers to enable the conversion and integration of vast hydrologic data into a central database for use in a GIS (Scott, 1991).

As suggested by Mancinelli (1986), the primary objective of any organization that wishes to optimize its operation is to implement an efficient data base management system. Central to any (integrated) water management and planning program is the need to collect, store, and organize the information that will serve as a base for evaluation of management alternatives and decisions (Akkad, 1989). The need for organized information is particularly important to developing countries which have scarce water resources that are strained to meet ever increasing demands (Munasinghe, 1991).

The investment that has been made to construct the required water treatment plants and distribution facilities in the Arabian countries of the Gulf Cooperation Council (GCC) is probably unprecedented worldwide (Hamdan, 1989). Towards proposing a rational water resources management strategy for the GCC countries, Hamdan (1989) recommends the development of computerized data management systems that can store all the water

resources data that has been collected in last three decades of water development projects in the region.

Development of water resources management plans can take on different priorities depending on the technological resources that are available. A fundamental premise to all water management and planning programs is the availability of information that describe the system being managed. The potential of interactive computer technology to accomplish management and policy making tasks has been well documented (Fedra and Loucks, 1985). The choice of which technology is employed to support management decisions is left to the engineers and decision makers who must design management and planning programs that help in understanding the dynamics of water resource problems today.

Spatial Data

Planners have always been fully conscious of the importance of location data when compiling an information system (Scholten, 1988). Physical planning deals explicitly with a large number of spatial units which need to be identified and labeled with their respective characteristics. The technology of Geographic Information Systems (GIS) shows promise of being a powerful tool for use in conducting water resources research and planning (Wright et al., 1990). Although commercial GIS products are still relatively expensive, the use of these systems

in support of water related decision settings is becoming more cost effective. Whittemore et al. (1987), utilized the ERDAS (Earth Resources Data Analysis System) to improve ground water resources planning efforts for delineating protection zones in Harvey County, Kansas. GIS systems have been shown to have the ability to display and graphically summarize both the input data for analytical models and results of application of management models using that data (Goulter and Forrest, 1987). The ability to display the results graphically improves the human-machine interaction which is generally accepted as being an integral part of multi-objective water resources analysis. The application of GIS technology is being applied extensively in all the natural resources fields including water resources. GIS technology is rapidly becoming a widely accepted tool in water resources management and planning (Worral, 1990).

Innovative applications of GIS technology in conjunction with remote sensing satellite data is also gaining popularity. Shih (1990) demonstrated the application of half-hourly visible and thermal infrared data from the Geostationary Operational Environmental Satellite (GEOS), in conjunction with the Scofield-Oliver method and GIS, to monitor rainfall in Florida. The results showed that the satellite rainfall estimations were well correlated to rain gage measurements.

The ability to obtain areal estimates of parameters over large areas as opposed to only point values make satellite imagery a useful and financially feasible tool when used in conjunction with GIS analysis. Inventory of land use and delineation of catchment basins are an integral part of spatial water resources evaluation. Remote sensing technology has long been recognized as a powerful tool to aide water resources managers and planners (Askew and Nemec, 1967). Recent advances in high resolution satellite imagery have resulted in extensive water resources research application using satellite imagery for spatial data analysis (Jagadeesha and Palnitkar, 1991). Kelly (1985) demonstrated the application of satellite imagery combined with a water rights GIS to assist in law enforcement of water rights and water use estimates in Arizona.

It is clear that GIS technology is playing a significant role in shaping water resource management and planning and will no doubt continue to do so. However, it has been asserted (Goulter and Forrest, 1987) that GIS should not be considered as the sole means for providing answers to complex water resources planning issues. Rather, it should be viewed as an important component of Decision Support systems by which information is transferred to the decision maker for consideration. Further, it has been suggested (Worral, 1990) that the issues surrounding the transfer of GIS technology and

techniques into policy making environments include such concerns as inherent suitability of the GIS to the policy making process. There are also concerns about the potential shifts in the power structure within organizations due to the lack of trained personnel who can effectively use all the techniques in GIS technology.

Hydrologic Models

A plethora of choices of hydrologic models exists for the simulation and quantification of both groundwater and surface water resources. Their efficacy and use is determined by the quality of input data and expertise of the user (Grigg, 1985). As rationalized by Van der Heijde et al. (1985) in their comprehensive discussion on numerical models and their application to water resources management, in theory the existing numerical models are capable of handling groundwater management problems. In reality, however, the successful application to solving such problems varies from one model to another. To date most of the hydrologic models produced are prediction models which may be subdivided into four categories: flow, subsidence, mass transport, and heat transport (Van der Heijde, 1985). Once a particular model has been chosen as the most suitable to the problem, the user must understand its structure, verify underlying assumptions, and regard its limitations in order to ensure successful application of the model. It is critical that technical experts

trained in the use of models be included in the management team.

The scarcity of trained personnel is generally the most acute problem faced by water resources management agencies in developing countries. Thus it is necessary for developing countries to encourage the development and expansion of programs designed to teach technical personnel how to better select and use models for addressing field problems as well as the capabilities and limits of newly developed modeling techniques (Van der Heijde, 1985).

It is often more practical and economically efficient for agencies to employ outside consultants to conduct any modelling work that is required. In this case communication of the results and particularly the limitations of the model need to be emphasized to the manager who usually lacks the technical background to fully understand the model. It is often quoted that technical experts state that their problems in applying models would be greatly reduced if managers would learn more about modeling (Van der Heijde, 1985). Managers need to have model results presented in a manner that is both meaningful and compatible with decision making. The uncertainties inherent in various decision alternatives are especially important to evaluate. The form of the output is also important; careful use of computer graphics and other displays may greatly enhance the utility of

model results (Van der Heijde, 1985). Models can clearly provide the basis for making many quantitative observations about the future, and provide a useful insight into the effects of current and future water development. The overall consensus, however, is that when used properly, and when results are properly interpreted, models can add a powerful dimension to the decision making process (Viessman et al., 1989).

Institutional Framework

A water resources plan consistent with the overall economic, social and environmental policies of the country concerned is an important element in ensuring that water resources contribute to the country's development objectives (U.N. Water Resources Series No. 65, 1989). The organization of water resources planning and management in a nation is generally a mix of centralization and decentralization.

The delegation of authority from the center, or power assigned to each subnational unit, varies from country to country and even within the same country according to a set of interrelated factors among which are the geographic and demographic size of the country, the social and political framework, the legal regime of water ownership and rights, the availability of water in relation to its use, regional diversity and traditional values and meanings of water for different societies (U.N. Water

Resources Series No. 65, 1989). This means that the mixture of centralized and decentralized planning modes must be dynamic and flexible enough to meet changing conditions in the future.

In attempting to rationalize the process of evaluating a societies values, customs and habits, institutional economists refer to a holistic approach known as "pattern modelling" or, as proposed by Radzicki (1988), "systems dynamics". A pattern model is a logically consistent "story" that details the institutional structure (laws, rule, regulations, customs, conventions) of a particular socioeconomic system and thus facilitates an understanding of why people living in the system behave as they do (Radzicki, 1988). These institutions order social relations (Bromley,1989) and, as such, affect actions taken by individuals as a part of the larger society.

System dynamics is based on the fundamental assumption that all living things that exist in a changing environment (institutions included) exhibit goal-seeking behavior. Systems dynamics specialists do not view goal-seeking as an activity that is pursued independent of the environment in which it takes place, but rather that goal-seeking behavior influences, and is influenced by, the many interrelated institutional structures or themes that define a particular socioeconomic system. That is, the values, rules, customs, habits, incentives, moral and

technological limits, material and information flows, and other psychological decision making factors of a particular socioeconomic system influence goals and, thus, actions taken (Radzicki, 1988). This approach is particularly useful for water resources managers who recognize the complexities of socioeconomic systems and their impact on water resources development.

Fundamental to any kind of water resources management and planning is the complete understanding of the way a system functions. Water resources management policies cannot be formulated in a vacuum: the complexity of human behavior and cultural norms are the most critical aspect to be considered in any policy making process. The central issue crucial to institutional policy making is the desired process of moving from "here" to "there"- from "what goes on here" (process) to "what ought to go on here" (other process) (Petr, 1988). Myrdal (1978) discusses the holistic nature of institutional analysis particularly in the area of policy formulation. He explains the fabric of society as a woven pattern that must be appraised and adjusted in as integrative a manner as possible. There is no value in a policy adjustment appropriate to a narrow set of considered indicators but ignorant of the interconnections of far greater human significance (Petr, 1988).

The effectiveness of the most sophisticated technological designs and comprehensive water resources

plans is a direct function of the level of institutional analysis considered in their formulation. Petr (1988) rationalizes that all proposals for policy adjustment, from whatever source, must be subjected to a test of synchronization between technological reality and institutional presumptions. A decision support system can play an important role in such synchronization.

Decision Making - The Multi Criteria Approach

Physical planning needs a coherent, institutional framework in which policy issues, objectives, measures and impacts are systematically brought together. The implementation of policy measures implies adequate insight into the set of feasible policy options (or alternatives), into the internal consistency of each operational policy option, into the flexibility and acceptability of each policy choice, and into the institutional framework of decision making (Nijkamp et al., 1990). Multiple Criteria Decision Making (MCDM) is both an approach and a body of techniques designed to aid people make choices which are in accord with their values in cases characterized by multiple, noncommensurate and conflicting criteria (Bogetoft and Pruzan, 1991). The rational for MCDM is basically contextual due to such factors as the multiplicity of values, objectives and criteria in the real world and the bounded rationality of real decision

makers, i.e. their limited capacities to collect and process information.

The ultimate goal of a MCDM model is to yield a "preferred" solution among a set of alternatives. The rational elements of MCDM are often described as values, objectives, criteria and preference (Bogetoft and Pruzan, 1991). Most real world planning contexts are characterized by multiple, and often conflicting goals or "objectives". Decision makers aim to accomplish many different things when they plan. These things may be of a qualitatively distinct nature. For example in determining a ground water recharge plan a decision maker may want to choose the best location, at a minimal cost and achieve maximum recharge. Objectives can be derived from certain more fundamental "values." In other words when considering the recharge site the decision maker could be motivated by the value of being able to replenish dwindling water supplies which would enable the continued existence of a public park which provides aesthetically pleasing environment for the neighborhood. One way to distinguish between the concepts is to consider values to be ends and objectives to be means to achieving the more fundamental values (Bogetoft and Pruzan, 1991).

Objectives are further characterized by measures of performance known as "criteria". In the case of ground water recharge the decision maker may operationalize the objective of a "good site" by considering the criteria of

infiltration rates and hydrogeologic characteristics or cost of buying the land needed. Clearly each objective may be characterized by a multiple of criteria, just as each value may lead to a multiple of objectives. Closely related to the notion of value, objectives and criteria is that of "preferences". Generally when a decision maker says "I prefer site A to site B", he presents a vocal expression to a cognitive synthesis of his multiple values, objectives and criteria. The close relationship of preference to the other notions is achieved via a "preference function". If a decision maker is to choose between alternative actions each of which is characterized by values of the criteria chosen to represent his objectives, then such a function allows him to rank the alternatives according to his underlying preferences. It follows from this prospective that his decision corresponds to the most preferred alternative (Brogetoft and Pruzan, 1991).

Practical applications of MCDM models are still in their infancy (Brogetoft and Pruzan, 1991; Nijkamp et al., 1990). An application of MCDM modeling was presented by Al-Rawahy and Smith (1990b) in evaluating the alternative options available to the country of Egypt to address their dwindling water supplies. The model that was applied in that case was MATS (Multi-Attribute Tradeoff System). This model is also presented in this study as

the primary mode of MCDM in the context of the decision support system that was designed.

The Multi-Attribute Tradeoff System, personal computer version (MATS-PC), was designed by Brown et al. (1986) at the United States Department of the Interior, Bureau of Reclamation. It is an interactive user-friendly program designed to assist in the analysis of multi-attribute evaluations or decisions. MATS-PC helps structure and analyze the choice among options or alternatives when many pieces of information must be considered for each alternative. MATS-PC helps reduce a decision's complexity by providing a means to

1. assess a decision maker's preferences or values which are relevant to the alternatives being considered,
2. record the relevant facts about each alternative, and
3. use the decision maker's values to evaluate alternatives, producing a ranking of the options.

Decisions made in the public sector can be very complex, and often have the added requirement that the basis for such decisions are made explicit and open to public review. MATS-PC can be used to provide an explicit framework for combining public input about values and goals with technical information about alternative strategies to meet those goals (Brown et al., 1986).

MATS-PC is a "certainty-based" decision analysis program, that is, it does not take explicit account of the probalistic risk or uncertainty. Uncertainty about the facts associated with the alternatives is incorporated via a sensitivity analysis, in which the impact of an alternative is varied systematically to examine the effect of those changes on the overall results. MATS-PC represents the various pieces of the decision problem as FACTORS, FUNCTION FORMS, WEIGHTS, PLANS, and IMPACTS. These are described as:

FACTORS: Factors are aspects of the decision that are important to the decision maker, the dimension on which the decision maker wants to base a choice. Any information about the alternatives which is considered important should be represented by a factor. MATS-PC required that all data or facts about alternatives be represented quantitatively. Many decision factors are already in numeric form, for example, water quality is expressed in mg/l chlorides or TDS (Total Dissolved Solids). If a factor is not already in numeric form, it must be described through the use of rating scales. For example, public acceptance of a project could be measured on a ten point scale, with 1 = "not acceptable" and 10="very acceptable". MATS-PC allows the user to specify up to 40 decision factors to describe the alternatives.

FUNCTION FORMS: Function forms are curves, defined by the user, that describe the desirability of different levels

of a factor. The decision maker defines a function form which describes how much benefit or utility is received from each level of the factor. The function form shows the relationship between each level on a factor and a scale of "utility" or worth.

WEIGHTS: Factor weights are the second device to represent the values or preferences of the decision maker. Weights represent the relative importance attached to each factor in the decision. The overall performance of a given alternative will depend not just on the alternative's rating on a factor, but also the weight placed by the decision maker on that factor.

PLANS: Plans is the general term used in MATS-PC to refer to options, alternatives, or choices among which the decision maker wishes to choose, up to 40 plans can be evaluated with each analysis.

IMPACTS: Impacts are the facts about each plan; the way a plan performs on a factor. Each plan will be represented by an impact for each decision factor.

Once the user has entered FACTORS,PLANS,IMPACTS, FUNCTION FORMS and WEIGHTS, an evaluation can be made which combines the values and the plan's facts to produce a ranking of alternatives. Mathematically this process is represented as

Plan Score (k) = (wgt(i)*(util(i,k))

where

k = Plan

nfac = number of factors in project

wgt(i) = standerdized weight of factor i

$$wgt(i) = \frac{wgt(i)}{wgt(j)}$$

Hence,

$$wgt(i) = 1.0$$

util (i,k) = the value of utility function of factor i, at impact k.

The first step in evaluating alternatives is to translate the facts about each alternative into subjective scores, or measures of utility, using the function forms. A subjective score indicates, on a 0 to 1 scale, how closely an impact approaches the best level of impact, as defined by the function form. A subjective score is calculated for each factor for each alternative. These describe the desirability, on a 0 to 1 scale, of each impact.

The next step in the evaluation process is to weigh the subjective scores on each factor according to the importance of the factor. To do this, the program multiplies each subjective score by the associated factor's weight. Finally, the overall score for each alternative is simply the sum of its weighted subjective scores on each factor.

The application of an MCDM model such as MATS-PC can aide the water resources planner in formulating rational

policies which reflect the values, habits, customs and laws of the community they serve. The models cannot be viewed as a replacement of the decision maker, but rather as with all models they can serve as a component of decision making in planning.

Interactive Computer Models in Decision Making

There exists a plethora of commercially available packages that are more commonly known as "Data Processing (DP) or Electronic Data Processing (EDP)", "Management Information Systems (MIS)", "Decision Support Systems (DSS)" and others that use imaginative acronyms (Hopple, 1988). Without delving into semantics, the DSS differs from the varying levels of information and data processing of the other systems in that a DSS revolves around a decision, rather than the information or data per se.

The emphasis is on flexibility and rapid response in a user initiated and controlled process of human-machine interaction, and support for personal decision making styles (Hopple, 1988). A further contrast is that DSSs are problem-oriented in that the problem and its context and the decision makers world view and distinctive information/analysis needs are the integral elements of reference. This problem-oriented process is designed to support problem-solving as a preface to making a decision and increase adaptation towards formulation of rational decisions/policies. Hollnagel et al. (1983) further

proposed that computer based information support can be viewed as potential tools or prothesis. A prothesis generally serves as a replacement for something missing, a human function, whereas a tool is a means or instrument used to achieve a goal. DSSs should function as tools, they should not be viewed as a replacement of the user but rather as a support and aid to amplify his or her judgement.

Formal definitions of a DSS can be quite restricted, but Sprague and Carlson (1982) offer a collective definition which describes a decision support system as an interactive computer based system designed to help the decision maker use data and models to solve "unstructured" problems. This is a more fitting definition of a DSS for water resources managers since the problems confronting decision makers are often broad and ill defined and require the synthesis of data originating from a variety of disciplines.

Technological developments in personal computers, large data bases, computer networks with real time data collection capabilities, user friendly interfaces and software and color graphics have reduced cost significantly and have thus contributed towards stimulating interest in the use of computers to support decisions in the water resources field (Hopple, 1988; Johnson 1985). As suggested by Chapra and Canale (1987), the use of improved DSS type technologies such as data

management, interactive computing, graphics, and simulation models can greatly enhance the communication between engineers and non engineers.

The interdisciplinary character of DSSs suggest that a rigid classification or standard for DSS architecture is futile (Hopple, 1988); however, a consensus among current workers (Hopple, 1988; Johnson, 1985; Newell et al., 1990) is that a DSS generally consists of three primary subsystems: a user-system interface to enable the decision maker to interact with the support system via an array of input routines and output technologies; a subsystem designed to store, manage, and facilitate the retrieval, display, and analysis of data; and a component that features a model (or, more commonly a group of models) to answer a host of user queries and perform a number of sensitivity (what if) and other kinds of tasks. Generally the three subsystems are interconnected; the degree and level of interaction between the three subsystems, however, varies between applications.

Decision Support Systems in Water Resources

In their lucid review of interactive computer technology pertaining to planning and modeling, Fedra and Loucks (1985) discuss the potential role of the interactive computer work station concept for producing a set of tools and techniques that allow the user to define, analyze, synthesize, and evaluate solutions to a problem.

A powerful and responsive tool should invite and stimulate a more experimental, innovative attitude towards problem solving and decision making.

Due to the increasing complexity and competition for water resources, water managers are finding an increased need for interactive computer models (such as decision support systems) to aid them in solving water problems (Stansbury et al., 1991). More than 200 public and private water experts from across the United States, Canada, England, France, Belgium, and Portugal participated at the 3rd ASCE Water Resources Operations and Management Workshop on "Computerized Decision Support Systems for Water Managers" held at Colorado State University in 1988 (Labadie et al., 1988). The presentation of papers over a broad range of subjects attests to the proliferation and interest in application of DSSs in the water resources management field.

Specific examples of DSS design and application in water resources cannot however be said to dominate the water resources management and planning literature. New and innovative applications of the varied tools that can be used in designing water resources management DSSs are, however, continuously being documented. In his design of a DSS for water transfer evaluations in south-central Nebraska, Stansbury et al., (1991) claims that his application of the analysis of a water model output by geographic information system (GIS) and subsequent trade-

off analysis of the GIS output by the application of a multicriteria decision making (MCDM) model with CP (Composite Programming) is unique. An innovative integration of GIS and expert system technology (Wright and Buehler, 1990) resulted in a spatial decision support system (SDSS) that can be used in managing land and water resources. Wright and Buehler, 1990, suggested that in the most straight forward case, a DSS that either uses spatial data as input, or produces a spatial solution or set of alternative solutions, may be classified as a SDSS.

The problem of managing estuarine water quality by characterizing the hydrological and hydrochemical properties that govern water quality has been addressed by designing a decision support system that prefers the object-oriented approach for data handling, mapping (using GIS technology) and programming (Arnold and Orlob, 1989). The DSS performs analysis of alternative management plans involving multiple simulations to find near optimum solutions. Another DSS to support estuarine water quality management has been developed (Camara et al., 1990). The system is implemented using Hypercard to provide answers regarding water quality and alternative uses of the estuary for different levels of water managers and decision makers. Hypercard allows the creation of applications for organizing, presenting and navigating through information. The information is synthesized in a set of electronic cards, each corresponding to a screen

image and selection of cards is made through the mouse. The user is able to design and write his own applications using Hypertalk, an object-oriented language. Hypercard appears to be a popular tool for implementing water resources management DSSs. Newell et al., (1990) also used Hypercard technology to implement a DSS for ground water contaminant modeling. The DSS (OASIS) developed a hydrogeologic database base upon 144 hydrogeologic settings from NWWA's DRASTIC System and data obtained from a national survey of 400 hydrogeologic site investigations across the country (Newell et al., 1988). The primary advantage with using OASIS instead of the conventional sequential approach to ground water modelling is that OASIS databases provide a built-in library of contaminant data and hydrogeologic settings (Newell et al., 1990). The OASIS DSS is a prime example of the importance of "information" to the decision making process.

Fundamental to most water resources DSSs is the availability of information or databases that describe the physical or socioeconomic system that surrounds the problem being addressed. The emphasis on processing information to assist decision making is clearly demonstrated in the DSS for local water management designed by Koch et al., (1986). The system is designed to evaluate alternative water distribution strategies and allows the user (manager) to exercise his experience in combination with the powerful computational tools and

complete data on the system. This approach reflects the premise that the backbone of a DSS is the information processing capability and the quality of the database it has incorporated. Indeed according to Alter's (1983) empirical case studies of over 50 DSSs, there is a class of DSSs that are "data-oriented", these perform data retrieval and analysis. As proposed by Hopple (1988), a decision support software may serve as a decision aid to assist in the process of weighing and comparing alternative options or as a foundation for decision modeling which provides help to the decision maker in selecting the most effective strategy for implementing a decision and exploring "what if" scenarios. In this context a well designed database management system can significantly assist, or at least provide the decision maker with the elemental foundations for weighing or evaluating decisions against the alternatives, qualifies as a type of DSS.

The initial challenge for the water resources manager remains to be to design a database that contains the relevant information which will later serve to support decision making applications.

CHAPTER III

BACKGROUND ON THE SULTANATE OF OMAN

The Sultanate of Oman is a relatively small country, located on the eastern coast of the Arabian peninsula. Oman has a desert climate, with exceptionally hot and humid weather along the northern, or Batinah, coast and hot and dry weather in the interior. The southern region, Dhofar, experiences light annual monsoons during the summer months. The land is a contrast of jagged mountains, green grasslands, and the sands of the Rub al Khali, or empty quarter.

The Sultanate has an estimated population of 2 million (Development Council, 1988). Muscat is the capital city, and the other major city is Salalah, located in the Dhofar Province in the south of the Sultanate. Among other towns are Sur, Nizwa, Rustaq, Ibri, and Sohar. Oman is bordered in the south by the People's Republic of Yemen, on the west by Saudi Arabia, and on the north by the United Arab Emirates. The Musandam Province of Oman, located on the Strait of Hormuz, is separated from the main part of the Sultanate by the United Arab Emirates (Figure 1). The eastern coast of Oman on the Gulf of Oman and the Arabian Sea is 1056 miles (1700 km) long.

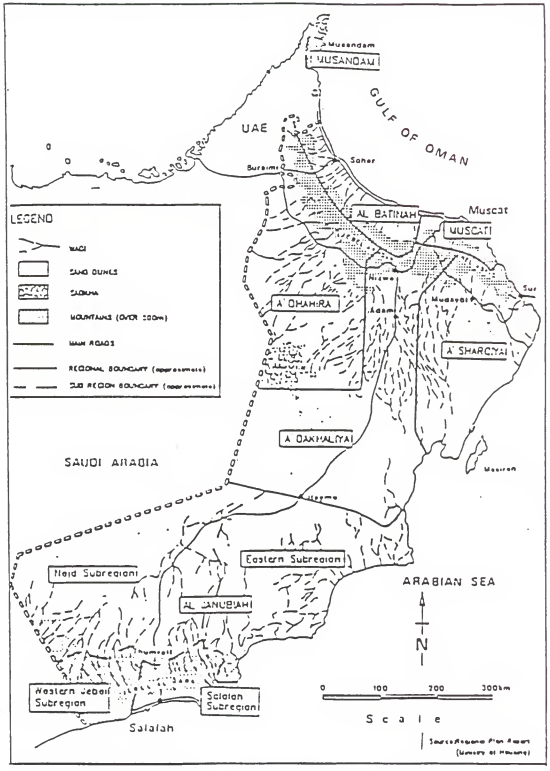

Figure 1. Map of the Sultanate of Oman

History of Water Supply System

Prior to the succession of His Majesty Sultan Qaboos in 1970, Muscat was a separated walled city, with the palace and other government buildings located inside the walls. Nearby villages were Mutrah, which was a one-hour walk over the mountain, from Muscat, and Ruwi, Wattayah, Qurum, Ghubrah, Hamriya, Riyam, Al Kwai, and Wadi Aday. Now these names designate districts within the greater Muscat area. In 1970, each of these villages was served by a series of water wells located in a nearby "wadi", a dry valley or drainage channel. The water distribution system in each of these villages provided water to mosques, the "wali" (governor's) house and office, and the residences of a few high government officials. The network in Muscat served the hospital and palace as well.

The forerunner of today's water distribution system was commissioned in April 1970 (Dawood et al., 1986). It consisted of three water wells located in Wadi Al Khawd that pumped to a 10,000-Imperial gallons (Igal), (45,460-L), reservoir from which it was repumped through a 12-in. (cement-mortar lined) ductile iron pipeline to Mutrah and Muscat, a distance of about 22 mi (35 km).

As new areas were developed in Mutrah, Ruwi, and Wadi Aday, the demand for water increased, so the system was expanded to meet those demands. By 1974, demand for water had increased dramatically as the capital area expanded. To meet the growing demand for water and electricity, the

government made a decision to construct a combined power generating station and desalination plant (a combined cycle plant), using the waste heat from power generation to assist in desalting seawater. The Ghubrah Power and Desalination plant is comprised of steam turbines and a multistage flash (MSF) seawater evaporator providing electricity and fresh water to the Muscat capital area. The plant, since its commissioning in early 1976, has been operated and maintained by Sogex International Ltd. for the Ministry of Electricity and Water. The Power and Desalination plant was built by Sogex under a turnkey contract. The evaporator was built by Demag using the basic design of Envirogenics Systems Company, U.S.A., a member of the Sogex group (Chalchal, 1979).

The sources of water for the greater Mutrah area are Ghubrah desalination plant, the Wadi Aday (eastern well field), the western well field, and Oman Refinery Corporation. The original Ghubrah desalination plant consisted of one unit that produced 4 to 6 Imgd (18 to 28 ML/d). Multistage flash distillation (MSF), which is common in most Arabian Gulf countries (Dawood et al., 1986), was used. A second MSF distillation unit, similar to the first, with a capacity of 6 Imgd (27 ML/d) was added to the plant in 1982, Figure 2 shows the Muscat area water supply facilities (after Dawood et al., 1986).

The intake for the seawater extends into the Gulf of Oman a distance of 2,953 ft (900 m). Seawater is drawn by

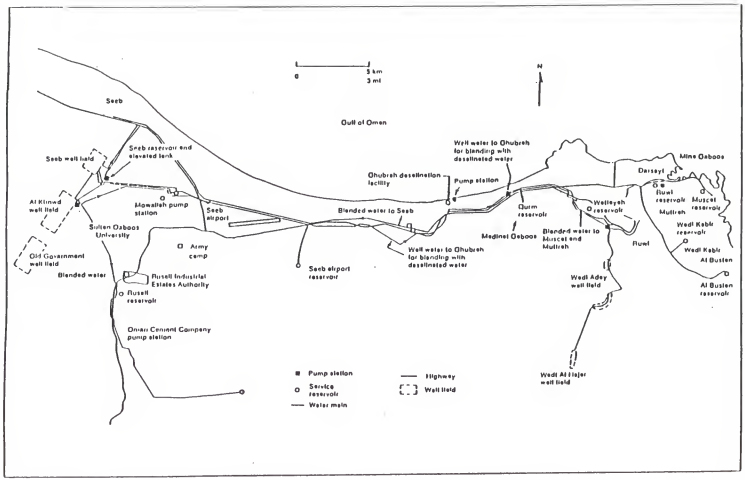

Figure 2. Muscat Area Water and Waste Water Facilities (after Dawood et al., 1986)

vacuum through four 80-in. (200 mm) pipes to a seawater pump pit located adjacent to the beach and on the plant site. Eight vertical centrifugal pumps, each with a capacity of 1.5 Igph (7,000 m^3/h), pump the water into the plant to commence the distillation process. The distillate from the plant is passed through a limestone bed and is chemically adjusted to lower the hardness of the water. The final product water fully meets the Omani drinking standards (Dawood et al., 1986). As the demand for water increases, the load control center calls for additional water by activating water wells in the eastern and western well fields. As the demand decreases, the wells are deactivated.

In April 1986, two additional MSF units, similar to the existing units, were completed and put into service at the Ghubrah plant. The total capacity of the Ghubrah desalination plant as of April 1986, was 23 Imgd (104 ML/d).

The Wadi Aday, or eastern well field, consists of 32 wells located throughout the length of the wadi, a distance of about 5 miles (8 km). The optimum pumping capacity of the field is 7 Imgd (32 ML/d), but the maximum pumping capacity for short periods is 10 Imgd (45 ML/d). The average electrical conductivity of these wells is 2500 micromhos/cm. The wells range from 144 to 442 ft (44 to 135 m) in depth. The use of this well field is closely monitored since over pumping will cause saltwater

upconing. Once the upconing has occurred, the well is lost as a sweet water well. Six wells in the lower end of the Wadi Aday have already turned brackish (Dawood et al., 1986). The brackish water from these wells is pumped to a 1.1 mil Igal (5,000 m^3) reservoir. From there the water is pumped to Ghubrah for blending with the distilled water. Thus if any wells become brackish, they are not lost but are used for blending (Dawood et al., 1986).

Three wells in the upper field are used to pump water into an area called the Hajar bowl. The bowl is a large open plain completely surrounded by mountains. A number of villages are located there. Currently, water is supplied to these villages through a tanker loading station, but a project contained in the third five-year plan (1986-1990) calls for a distribution network and storage facilities in the bowl to provide water services to these homes (Dawood et al., 1986).

The western well field, situated west of the Seeb International Airport, is located in Wadi Al Khawd. It consists of three sections: the Old Government section, the Al Khawd section, and the Seeb section. The old government section has 14 wells ranging in depth from 213 to 312 ft (65 to 95 m). The well casings are 8 and 10 in. (200 and 250 mm) in diameter. All wells are screened. The optimum capacity of this section is 0.8 Imgd (3.6 ML/d) with a maximum capacity of 1.2 Imgd 95.4 ML/d). The electrical conductivity averages about 1,350 micromhos/cm.

The Al Khawd section is downstream of the Old Government section and below the new Al Khawd recharge dam. It consists of 18 wells, spaced at minimum intervals of 1312 ft. (400 m). The wells are about 230 ft (70 m) deep. All the wells are cased and screened with 10-in (250 mm) casings. By agreement with the Ministry of Agriculture and Fisheries, which built the recharge dam, water is pumped from only 12 wells at any one time, keeping six in reserve. All wells are pumped using a rotating schedule. If an emergency occurs and additional water is needed, all 18 wells can be activated. The optimum capacity of the 12 wells is 3 Imgd (13.6 ML/d) with a maximum capacity of 4 Imgd (13.6 ML/d). The average electrical conductivity is 1300 micromhos/cm.

The Seeb section of the western well field is downstream from the Al Khawd section and recharge dam. It consists of 12 wells ranging from 8 to 10-in (200 to 250 mm) in diameter. All wells are cased and screened. Their depths range from 189 to 361 ft (88 to 110 m). The optimum capacity of this section is 3 Imgd (13.6 ML/d) with a maximum capacity of 4 Imgd (18 ML/d). The average electrical conductivity is 1,200 micromhos/cm. Six additional wells are located outside the physical boundaries of the western well field, but because of their proximity to the area, they are considered part of the well field.

The total groundwater resources for the capital water system is 82 water wells with an overall optimum capacity of 13.8 Imgd (62.7 ML/d) and a maximum capacity of 19.2 Imgd (87 ML/d). The average temperature of the groundwater at the discharge head of the wells is 93° to 95°F (34° to 35°C).

The last source of water is the excess distilled water produced by the Oman Refinery Corporation (ORC), which has two MSF distillation units to produce water for the refinery. In October 1984, Ministry of Electricity and Water signed a contract with ORC to purchase excess distilled water. The treated water is pumped into the greater Muscat water distribution system in the Qurum Heights area. The contract calls for a maximum quantity not to exceed 0.5 Imgd (2,200 m^3/d). The water sources and characteristics for the capital area are summarized in Table 1.

The Ministry of Electricity and Water, established by royal decree in 1978, is responsible for the supply of potable water (and electricity) for the Sultanate in the greater Muscat area, as well as rural areas and the interior, except for the Musandam Province, the Al Buraimi area, the Dhofar Province, and the Sohar region, which are under various jurisdiction.

Table 1. Desalination Plant Sources for the Capital Area

Desalination Plant Sources for the Greater Muscat Area				
SOURCE		QUANTITY (Imgd)	NUMBER OF MSF UNITS	
Ghubrah Desalination Plant		23	4	
Oman Refinery Corporation		0.5	2	
	GROUNDWATER SOURCES			
SOURCE	NUMBER OF WELLS	DEPTH (ft)	OUTPUT (Imgd)	CONDUCTIVITY (umho/cm)
Eastern well field:				
Wadi Aday	32	144-442	7	2500
Western well field:				
1. Old govt'	14	213-312	0.8	1350
2. AL Khawd	18	230	3	1300
3. Seeb	12	189-361	3	1200
TOTAL	*76		13.8	

*There are six other wells whose output is not identified.

Production and Consumption

The State Development Council publishes the Statistical Year Book, and in 1988 the figures were published related to water production and consumption for the Muscat area from 1970 to 1987. When the data is graphed to present the annual production versus consumption of water for the Muscat area (Figure 3, adapted from The Statistical Year Book, 1988), it can be seen that the trend from 1980 to 1987 has been for the production of water to exceed the consumption by an average of 32 percent. It is not clear what is done with the surplus water that is produced. The State Development Council has estimated the greater Muscat area population to be 350,000 in 1985. Using this figure, the daily per capita consumption is about 60 (US) gal (226.58 L). For planning, the Directorate General of Projects at the Ministry of Electricity and Water has been using 66 gal/day - 250 L/d - (Dawood et al., 1986). Total water production for the Muscat capital area is shown in Table 2 (after WASH report, 1986). Production costs for the desalinated water are not readily available, however it has been estimated that in 1981 the cost for desalinated water in Oman was $5.15/1000 gallons, in 1990 dollars (Stanley Consultants, 1981). However, the average cost of desalinated water in the middle east, which supplies a large portion of Saudi Arabia's potable water, is reported to be $6.79/1000 gallons (Ukayli et al., 1988).

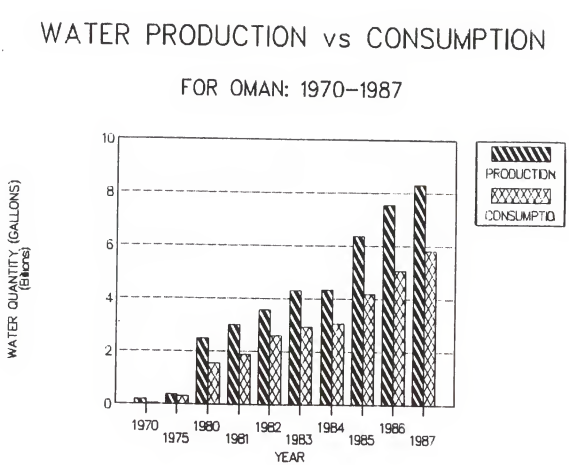

Figure 3. Water Production vs Consumption for Oman (Adapted from Development Council, 1988)

Table 2. Total Water Production for Muscat - June 1986

SOURCE	AVG.PRODUCTION		% OF TOTAL
Ghubrah Desal'	21.5	mgd	96.3
Oman Refinery	0.3	..	1.4
Western Wells	0.0	..	0.0
Eastern Wells	0.5	..	2.3
TOTAL:	22.3	mgd	100

Governmental Agencies Involved in Water Resources

The Water Resources Council (WRC), a national water policy coordinating committee, was established in 1974 and is chaired by the Sultan. The Deputy Chairman is the Minister of Agriculture and Fisheries. Members include the Ministries of Electricity and Water, Interior, Land Affairs and Municipalities, Communications and Petroleum and Minerals. All major water questions come before the Council for decision, and national rules and regulations such as those for permitting of new wells are issued by the Council. Supporting the Council, in a technical capacity, is the Public Authority for Water Resources (PAWR) which was formed in 1979. The Chairman of PAWR is the Minister of Electricity and Water. Attached to PAWR and acting, in some respects, as the Secretariat, are water technical experts from the U.S. firm Tetratech International. Studies and research efforts are carried out by PAWR to investigate and measure water resources.

The following is a list that describes the governmental agencies involved in water resources and their responsibilities:

1. Water Resources Council and Secretariat

   Makes recommendations to the Development Council on water policy. It provides coordination in water resources activities to all other agencies; assesses overall water availability on the basis of plans and proposals submitted by various agencies; assesses the feasibility of artificial recharge; evaluates the dangers of saline intrusion; manages the water resources development through operation of a permit system.

2. Office of H.E. Wali of Dhofar

   Supplies water to the city of Salalah and to villages in Gebel Qarah; collects basic hydrologic and meteorological data in Salalah.

3. Ministry of Education

   Provides training and scholarships to students in water resources.

4. Ministry of Commerce and Industry- Laboratory

   Conducts chemical and physical analyses of water samples; develops water standards for the Sultanate.

5. Ministry of Commerce and Industry - Directorate of Industry

   Designs and constructs (or approves) water supply works for industrial development.

6. Ministry of Health

   Monitors water quality for human consumption; its laboratory conducts chemical and bacteriological analyses of water samples.

7. Ministry of Land Affairs and Municipalities

   Provides and manages waste water disposal facilities in all cities of the Sultanate; provides drinking water to smaller municipalities.

8. Ministry of Agriculture and Fisheries - Falaj and Irrigation Maintenance Department

   Performs, or finances, repairs on the aflaj; it reclaims land for agricultural purposes.

9. Ministry of Agriculture and Fisheries - Water Resources Dept.

   Evaluates and assesses availability of water for agricultural purposes; plans agricultural development projects; collects basic hydrologic data as part of a national water survey.

10. Ministry of Defense

    Supplies water to military camps and installations.

11. Ministry of Electricity and Water

    Supplies drinking water to the larger cities and municipalities.

12. Ministry of Social Affairs and Labor

    Supplies drinking water to new housing developments outside the existing cities.

13. Diwan of H.M. for Protocol

    Supplies drinking and irrigation water to the properties of His Majesty.

14. Ministry of Communications

    Collects hydrometeorological data through a network of observation stations; conducts hydrologic studies for road designs.

15. Ministry of Awqaf (Islamic Affairs)

    Maintains a register od awqaf properties, including water rights.

16. Petroleum Development (Oman)

    Supplies water to its own facilities and residential areas.

17. Ministry of Interior

    Through the offices of the local Walis (chiefs) it acts as the first judge in settling disputes concerning water rights.

18. Ministry of Diwan Affairs

    Has an active unit for environmental protection including safeguarding the water resources.

It should be noted that since 1986 when this list was compiled (after, U.S. AID., 1986), amendments have been declared by Royal decree. The most significant amendment was the Royal Decree to establish the Ministry of Water

Resources in early January 1990. The ministry basically takes over the tasks of the Water Resources Council and PAWR.

Water Resources Management in the Sultanate of Oman

The Arabian countries of the Gulf Cooperation Council (Kuwait, Saudi Arabia, Oman, Qatar, Baharian and the United Arab Emirates) have made impressive accomplishments in the water sector in the past two decades by developing water supply sources to meet their national demands (Hamdan, 1989). It has been noted however (Akkad, 1989; Hamdan, 1989), that despite these accomplishments the scarcity of natural sources of useable water in this region has contributed to impose important limitations on the national development of the GCC countries. Further the extent to which the natural water resources of the GCC countries are recognized as being a shared resources (deJong, 1989), there still remains to be no clear plan that coordinates the water development of the region.

Oman has become the first country in the Middle East to establish a government ministry entrusted solely with managing the nation's water resources (Stephens, 1990). The Ministry of Water Resources was established by Royal Decree 100/89 in October 1989. Prior to this, Royal Decree 82/88 was released in November 1988. The decree states that "The Sultanate's water reservoir is considered as public national wealth to be exploited...according to

the Government's instruction" (WASH, 1990). This decree established that all ground water extraction, for any purpose, may be regulated by the government. The decree 100/89 establishing the Ministry of Water Resources was released in order to establish a central authority for administration of the Sultanate's water resources.

The new ministry was formed from the existing Public Authority for Water Resources. The decree included the following directives to Ministry of Water Resources: (WASH, 1990).

- Establish a "...plan for the development (and conservation) of water resources..."
- Collect and manage water resources data.
- Undertake research to determine the best methods for conservation and use of water resources.
- Maintain hydrologic and hydrogeologic monitoring networks.
- Issue permits for new wells.
- Train Omani personnel working within the Ministry.

These directives are daunting when it is considered that there are eighteen governmental agencies concerned with water resources in the Sultanate. However the need to coordinate the activities of the different agencies towards effecting a national water resources management strategy has been recognized (Mott Macdonald, 1990).

Several major studies of the nation's water resources were undertaken in the 1970s. Agriculture, including water use and resources aspects, was studied by FAO/UNDP

in 1972. A comprehensive water resources survey of Northern Oman was conducted by Gibb (1976) and ILACO (1975) and later by Doyel et al., (1984). The University of Durham (1978) conducted a series of research and development surveys on northern Oman. Halcrow & Partners conducted the surveys and investigation into land and water resources development of the southern region (1975). The general conclusion of all these reports was that further development should proceed with caution and there was little optimism that large additional sources of water could be found. Since the late 1970s, numerous investigations have been undertaken for specific development projects as well as more detailed studies of specific areas (Mott MacDonald, 1990). The view expressed in the earlier reports that water resources were severely limited has generally been confirmed. Despite these findings there has been considerable development of groundwater for both agriculture and potable supplies which has resulted in serious deficits in many areas.

In December 1989 the Government of Oman, represented by the Ministry of Water Resources commissioned Mott MacDonald International in association with Watson Hawkesley to prepare a National Water Resources Master Plan for the country. The general objective of the investigation was to formulate a plan for sustainable development, management and conservation of water resources of the country. This was to include assessment

of water resources, projections of future demands, evaluation of alternative development and management options and a review of the institutional (including) framework required for implementation of these options.

The current status of water resources management in Oman is reflected by the struggle of the Ministry of Water Resources in attempting to adhere to the National Water Resources Master Plan as recommended by the Mott MacDonald report. To date no "water resources management" policies have been declared by the Ministry of Water Resources. The main tasks that seem to be occupying the ministry are concerned with water assessment projects which are geared towards collection of data, and internal organizing of the ministry itself. One of the primary projects of the ministry has been a national well registration and inventory program (Ministry of Water Resources, 1990). This has proved to be a monumental task since the primary phase of the program has revealed that there are 177,000 "registered" wells in the country. To improve data organization the ministry is implementing a database management program as described by WASH (1990). Coordination of district offices and monitoring well data is of primary concern towards these efforts. The activities of the Directorate of Water Resources Management and Planning, are dominated by well permitting claims and local water disputes over water rights. Efforts to establish a GIS unit which records spatial data

and hydrogeologic characteristics are seriously hampered by a lack of qualified staff and directives from the water management team. Implementation of recommendations from management "experts" within the ministry have not received serious consideration or discussion. The (former) Deputy General of Water Resources Management at the Ministry of Water Resources, laments that the "Ministry of Water Resources (MWR) and its predecessors, have over the years collected a large amount of raw data...the "assessors" prefer to continue to do more and more basic data collection and to stay away from anything that involves deciding who shall use the water...an ongoing flow of contracts for projects covering activities...and an awareness of the Ministry's ludicrous "management by project" ...there are very few signs of any (management) action to do something with those data. There is no thinking or analysis going on...many aspects of the water sector will continue to be political in nature..." (Dr. R. DeJong, personal communication, July 24th, 1991).

It is clear that the concept of water management per se, on a national scale at least, is still in its infancy in Oman. However, the problems faced by the Ministry of Water Resources in Oman are certainly not unique. Water resources managers in the United States continue to recognize that water management is a highly political issue (Ingram, 1990; Viessman, 1989). The continued development and existence of countries like Oman, which

have very finite water resources, depends on the ability of the decision makers to formulate policies and decisions that support the ideal of "sustainable" development.

CHAPTER IV

WATER RESOURCES OF THE BATINAH COAST

"Al Batinah" is an alluvial plain on the northern and eastern flanks of the Oman mountain arc (AL Hajar mountains). Mean monthly temperatures range from 25 to 40^{0}C in the summer and 13 to 28^{0}C in the winter months. Mean rainfall at the coast is about 125 mm/year while potential evapotranspiration is 3414 mm/year (Speece, 1981).

The most striking feature of the Batinah is the narrow continuous strip of cultivation and settlements stretching the length of the coast on the seaward side of the coastal highway. Dates are the main crop, covering 70 to 80 percent of the cultivated area. About 30 percent of the palms are interplanted, mainly with limes and bananas. Lime orchards occupy approximately 10 percent of the land. The remaining hectares are planted in onions and other vegetables, melons, and tobacco.

In the coastal area where the depth to groundwater is less than 8 m, thousands of wells have been dug to support an almost continuous belt of agriculture over a distance of 270 km from Wadi Rusayl in the southeast to the United Arab Emirates in the northwest (Figure 4). The Batinah

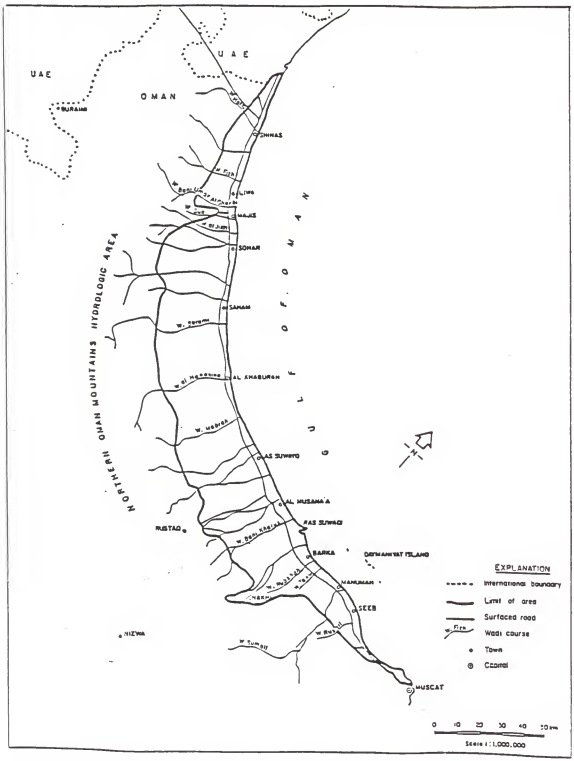

Figure 4. Map Showing the Batinah Coastal Plain (after Doyel et al., 1984)

belt constitutes approximately half of the country's agricultural area (Stanger, 1984).

The most exhaustive studies of the Batinah hydrologic area were conducted by the Public Authority for Water Resources (PAWR). The 1984 PAWR report 83-1 written by Doyle et al., describing the hydrology of the Sultanate of Oman, includes a comprehensive description of the Batinah area.

From its beginning east of the Seeb Airport, the Batinah gradually widens to 30 kilometers at Barka, thereafter maintaining its width for 50 kilometers northward to Suwayq. The Batinah is approximately 20 kilometers wide for the next 100 kilometers northwest from Suwayq, narrowing in the last 65 kilometers to 10 kilometers before narrowing out abruptly at Khatmat Malaha.

The Batinah hydrologic area can be subdivided into two general zones paralleling the coast, based on differing geomorphological characteristics (see Figure 5). The first, a piedmont zone, extends seaward from the base of the mountains to the terminus of a series of stream terraces. The elevation at the upper edge of the piedmont zone varies from 70 meters above sea level near the northern border to over 200 meters above sea level inland from Barka. This zone covers about 3,270 km^2, or 56 percent of the Batinah area.

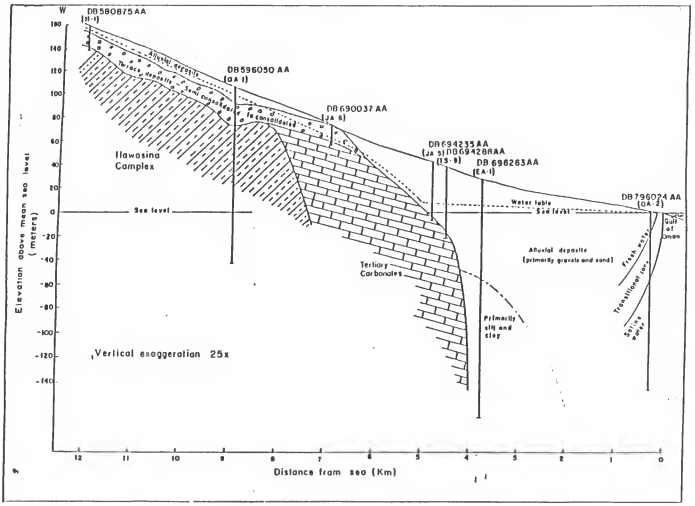

Figure 5. Schematic Geologic Cross Section of Batinah Hydrologic Area (after Doyel et al., 1984)

The second zone, the coastal plain, is located between the piedmont zone and the sea. It includes the alluvial deposits of the present wadis, the coastal dunes, and fertile soils which support the majority of the agriculture within the Batinah area. There is a gradual transition at the upper end of this zone into the piedmont zone. The coastal plain zone comprises the remaining 2,550 km^2, or 44 percent of the Batinah area.

Climate and Rainfall

The climatic year of the Batinah hydrologic area can be divided into two distinct periods. The winter months of November to April are characterized by an extensive low pressure area over the Indian Ocean and airflow from the northwest. The summer months from June to September feature a monsoon airflow from the southwest.

Heavy and widespread rainfall in the winter can result if the northwest airstream is interrupted by disturbances moving down from the north. In the summer, the southwest airstream provides frequent rainfall in the Oman Mountains caused by the orographically ascending air mass, but it is rare for this rainfall to reach the Batinah area. Monthly rainfall for Seeb for the period 1976-1981 and for Sohar for 1974-1981 are given in Table 3.

Table 3. Monthly Mean Rainfall at Seeb and Sohar, in millimeters, (after Doyel et al., 1984)

Seeb

Year	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	Total
1976	16.0	42.5	57.0	0.3	—	—	2.4	—	—	—	—	4.1	152.3
1977	50.5	27.0	4.6	14.0	0.9	9.9	—	—	—	—	75.7	—	182.6
1978	10.7	11.4	12.8	—	—	—	—	—	—	—	7.0	—	41.9
1979	8.3	2.2	—	—	—	—	—	—	—	—	—	8.5	19.0
1980	1.5	2.0	0.2	—	—	—	—	—	—	—	—	—	3.7
1981	17.0	—	23.5	—	69.2	—	—	—	—	—	—	—	109.7
Mean	17.3	14.1	16.3	7.3	11.6	1.6	0.4	0.0	0.0	0.0	13.7	2.1	84.8

Sohar

Year	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	Total
1974	0.6	71.6	2.7	0.6	—	—	—	—	—	—	—	2.2	77.7
1975	2.6	44.5	—	—	—	—	—	6.2	—	—	—	—	53.3
1976	2.5	118.0	51.9	55.2	—	—	—	—	—	8.2	—	17.3	253.1
1977	68.1	26.3	2.6	38.7	10.9	—	—	—	—	—	17.6	0.2	164.4
1978	—	34.2	6.5	2.0	—	—	3.6	—	—	—	—	0.3	46.6
1979	21.4	—	1.5	2.3	—	—	—	—	—	36.6	0.7	58.4	120.9
1980	1.7	2.2	3.9	1.2	—	—	—	—	—	—	0.8	—	9.8
1981	4.8	—	1.5	18.2	12.6	—	—	—	—	—	—	—	37.1
Mean	12.7	37.1	8.8	14.8	2.9	0.0	0.5	0.8	0.0	5.6	2.4	9.8	95.4

Occurrence of Groundwater

In the Batinah hydrologic area, alluvial deposits are the main aquifer, supplying water to about 8,100 hectares (20,250 acres), of irrigated land in the coastal garden belt. In addition, this aquifer supplied 15 percent of the greater Capital area water demand in 1982, according to figures developed by the Seeb District Office of PAWR. Although alluvial deposits occur in both the piedmont and coastal plain zones, the extensive deposits of the coastal plain are the principal source of supply for agricultural and domestic uses. A schematic representation of the hydrologic cycle in the Batinah hydrologic area is shown in Figure 6.

Salinity in the Coastal Plain Aquifer

The salinity of groundwater in the coastal plain aquifer normally is low in a direction landward from the coastal agricultural belt, usually having a specific conductance of 1,000 micromhos/cm or less. On the seaward side of the gardens the conductivity increases to as much as 20,000 micromhos/cm. A survey by PAWR personnel of the specific conductances of water from wells has identified salinity trends along the entire Batinah coast (Figure 7). The measurements show that the salinity of coastal groundwater is greater than 6,000 micromhos/cm for all of the eastern Batinah. In these areas, withdrawals of groundwater have exceeded recharge reaching the area that

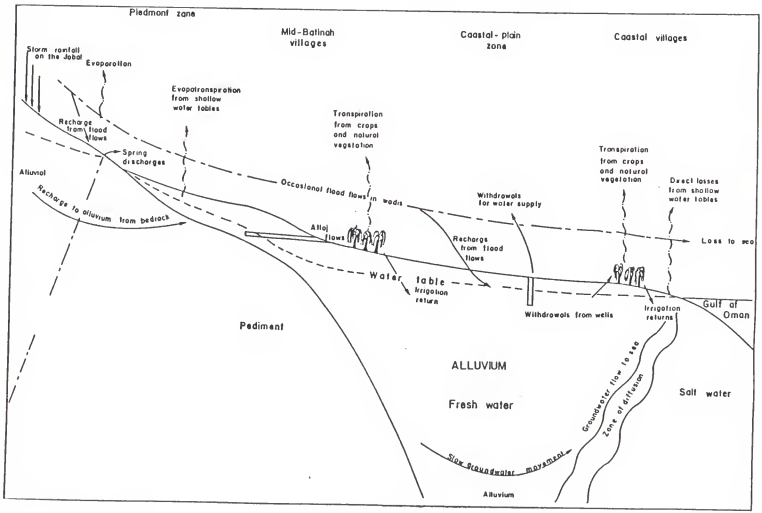

Figure 6. The Hydrologic Cycle in the Batinah Hydrologic Area (after Doyel et al., 1984)

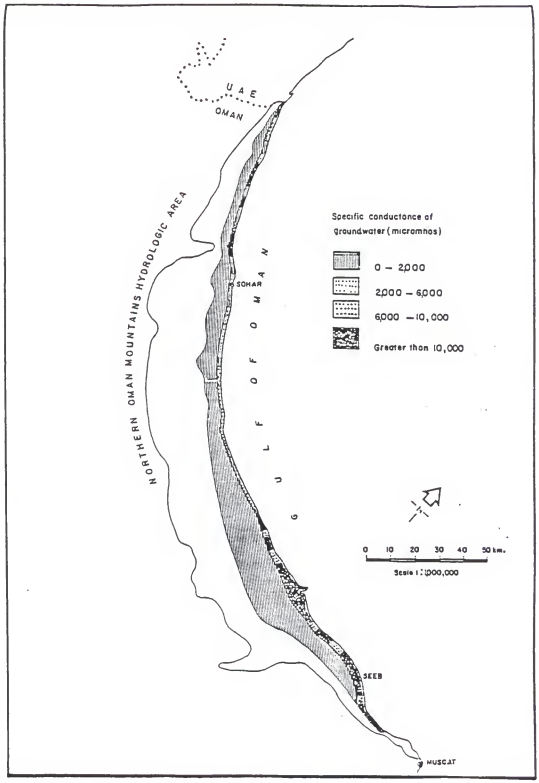

Figure 7. Chemical Quality of Ground Water in the Batinah Hydrologic Area (after Doyel et al., 1984)

salt water encroachment has occurred. In six small areas located along the central and northern coast, the conductivity of water at the coast is below 2,000 micromhos/cm, indicating that flow of fresh groundwater at these points is sufficient to overcome the danger of salt water encroachment.

The Study Area

The study area chosen is located along the eastern part of the Batinah coastal plain (see Figure 11). The coordinate location of the area is N23° 42'/E58° 53' and N 23° 36'/E 58° 22'. The eastern most point of the study area is located at Ghubbat Al Hayl and the western most point is located at Barka. This area is a rapidly developing part of the Batinah and is becoming increasingly urbanized. Its proximity to the capital area has made it a prime location for a sprawling suburb. There is a clear trend of changing land use patterns from Ghubbat Al Hayl westward. Much of the traditional date palm farming in the Al Hayl area has been abandoned due primarily to acute saline water intrusion and due to the high demand for open land by the city dwellers. The incentive to sell the traditional farm land to urban dwellers was particularly high during the oil boom decade between 1975 and 1985. Interspersed between residential developments there still exists pockets of traditional date palm farming. Westward toward Barka among the

traditional date farms are a growing number of "hobby" farmers who are generally city dwellers who have bought existing farms or were allotted land for agricultural development by the government.

The hobby farmers are distinctive in that they can afford to employ laborers to tend the farms and are beneficiaries of the government's agricultural loan programs. These programs were designed to encourage the private sector to become involved in the agricultural development of the Batinah region. The government offers interest free loans to purchase pumps, drill for wells, fertilizer, seedlings etc. The objective is to make the Batinah area "the bread basket of Oman". The social and political value of this project is debatable but is however beyond the scope of this study. However, the impact on the water resources of the area is of concern and one of the primary goals of this study is develop a decision support system that can be used to evaluate these impacts.

All the agricultural activities of the study area are supported by ground water development. The consumptive use for the whole Batinah area has been estimated at 788 mgd (Doyle et al., 1984). A majority of the farms are irrigated by dug wells but an increasing number of farmers are turning to drilled wells.

The government has been very conscious of the impact of the rapid development in this area. In an effort to

discourage the exploitation of the finite ground water resources of the area the government has constructed a main water pipeline from the Al Ghubrah desalination plant along the coastal highway to Barka. Beginning in 1985 an extensive program of supplying mains water to the residential parts of Al Hayl was begun.

As new residential areas are developed, the pipe network is expanding to service these areas accordingly. The government through the activities of the Ministry of Agriculture and Fisheries has also embarked on an ambitious artificial recharge dam program for the Batinah area. In 1986 the first artificial recharge dam was completed at Al Khawd. Construction of more recharge dams along the Batinah region are currently under way. The evaluation of total recharge and efficacy of the dams is carried out by the Ministry of Water Resources. It is estimated that the Al Khawd recharge dam will add almost 0.9 billion gallons annually to the ground water resources of the Somail basin along the Batinah coast (Stanley Consultants, 1981).

The National Water Resources Master Plan (Mott MacDonald International Ltd., 1990), included an evaluation and projection of future population and water demand for the six administrative regions of Oman. The fastest growing region is shown to be the Batinah (Figure 8, adapted from Mott MacDonald, 1990) with a projected population of 868,492 by the year 2010 and a gross water

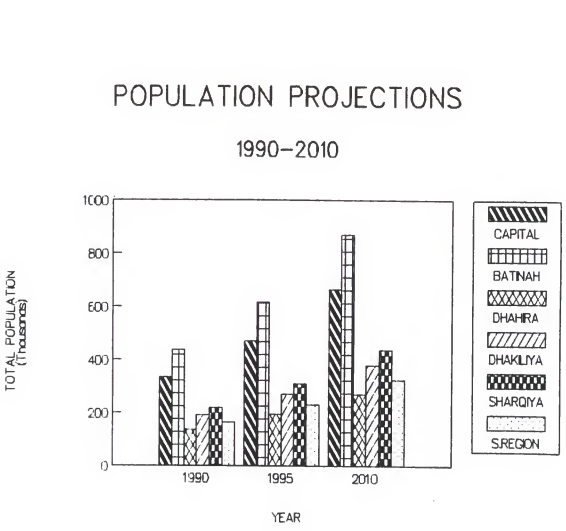

Figure 8. Population Projections (adapted from Mott McDonald, 1990)

demand of 12.6 billion gallons per year (57.4 MCM/year) (Figure 9, adapted from Mott MacDonald,1990). It is interesting to note that although the Batinah area is projected to have the greatest population increase, its corresponding water demand is almost half that of the capital area. This anomaly could be because the coefficients that were used by Mott MacDonald produced the more conservative estimate for the capital area. Alternatively, it could be due to the assumption (again by Mott MacDonald) that a combination of water saving irrigation technologies and better on site farm management would result in the rural area of the Batinah being more water efficient than the urban areas, who would tend to have more "wasteful" recreational and domestic water consumption habits (i.e. washing machines, gardens, swimming pools and car washing etc.). However, with much of the coastal aquifers already suffering acute salt water intrusion, it is clear that new sources will have to be explored to meet this demand.

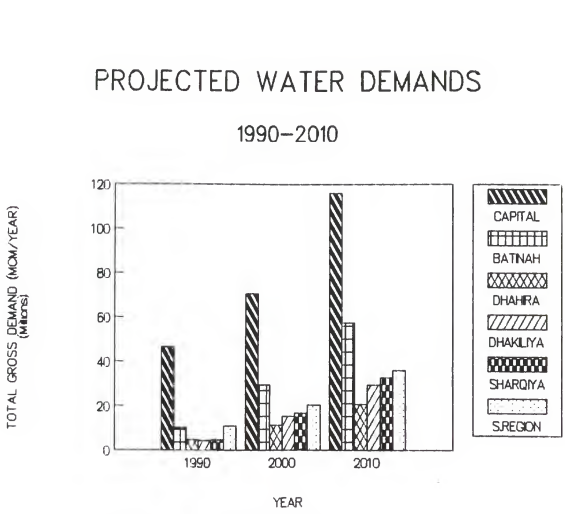

Figure 9. Projected Water Demand (adapted from Mott McDonald, 1990)

CHAPTER V

METHODOLOGY

The application of DSS in the water resources management field has been encouraged by the affordability of PC graphics and database software. Local water management districts can now effectively utilize a wide range of software and apply them in the design of DSSs to support water management policies. Several examples of DSSs designed to support water management exist (see Koch et al., 1986, Johnson, 1986, Newell et al., 1990).

The design of DSS is directed by the application that the user wishes to make. A DSS can be as dynamic in its application as the user determines. The whole idea behind a DSS design is that it should be efficient in its manipulation and display of the data. Attributes and constraints should be factors which are readily discernable, this is generally accomplished by employing graphics packages which display the data in color maps or charts.

In this study Geographical Information System (GIS) technology in conjunction with supporting database, decision/policy analysis and ground water modelling software was applied to produce a DSS for evaluating and

supporting water resources management strategies and policies in the Sultanate of Oman.

The DSS package that was designed for this study comprised of five basic components as follows:

1. Digitized base maps of the study area generated from ARC/INFO.
2. Remote sensing data (Satellite imagery).
3. Supporting water resources database designed for the study area.
4. Appropriate hydrologic modelling capabilities.
5. Policy decision analysis with MATS.

The interaction and feedback of the various components of the DSS are described in Figure 10 illustrating the DSS architecture.

Study Area

The study area was defined along the eastern Batinah coast of northern Oman (Figure 11). The coastal coordinates of the study area are: $N23^0$ E42'/$E58^0$ 53' - $N23^0$ E36'/$E58^0$ E22'. The landward delineations do not exceed 10 km landward from the coastline, producing a total study area of about 450 km^2.

GIS Layers

The layers that will comprise the GIS will be:

1. Land use
2. Vegetation
3. Hydrogeology

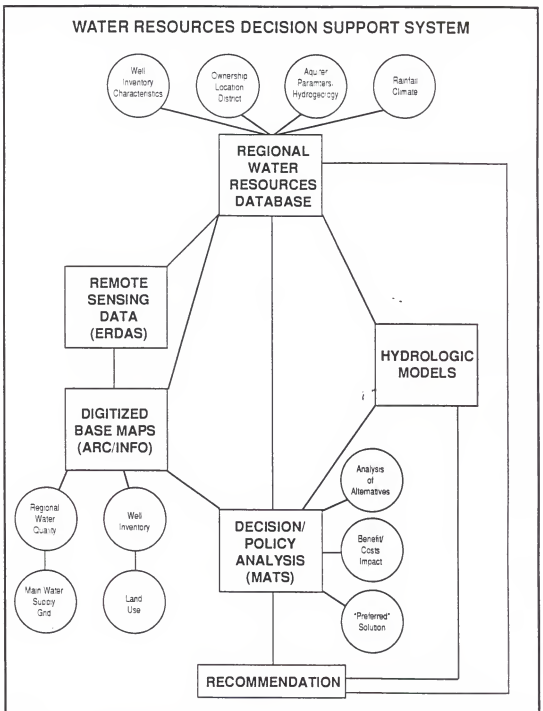

Figure 10. Data Synthesis and DSS Architecture

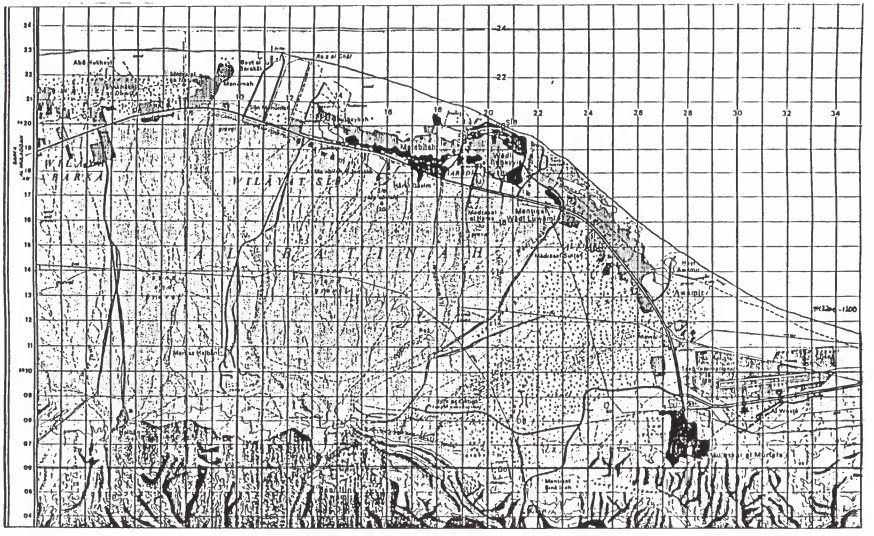

Figure 11. Map of Study Area

4. Well inventory
5. Water rights, jurisdiction districts
6. Water quality zones
7. Wadis (catchment basins), flood zones

The scale of all maps was maintained at 1:100000. All coordinates will be expressed in easting and northing.

Satellite Imagery

Satellite digital data tapes were acquired from EARTHSAT CORP. in Rockville, Maryland. They were processed on the ERDAS image processing system in the Remote Sensing Lab in the Reed Lab (Department of Civil Engineering).

Supporting Database

A relational database was designed to contain the data that was collected from the field investigations and the review of Ministry of Water Resources data files. The DBASE IV database package was used to house the database. Figure 12 shows the entity relationship diagram for the DSS database schema.

Instruments/Equipment

1. Global Position System (GPS) technology was employed to perform well inventories. A MAGELLAN GPS NAV 1000 PRO™ was utilized for this function.

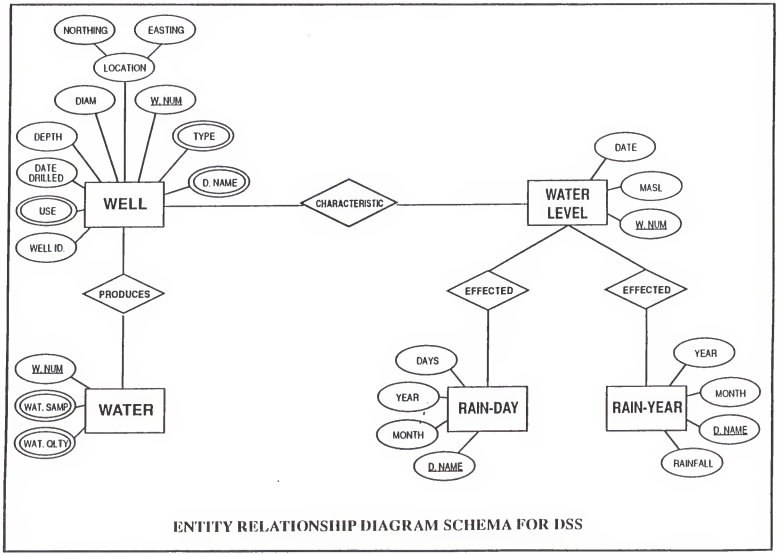

Figure 12. Entity Relationship Schema Diagram for DSS Database

2. ARC/INFO package was used for all digitized spatial data.
3. The field work was carried out in Oman. All supporting field materials e.g. transportation, computer facilities, laboratory facilities, well sampling equipment, were provided by the Ministry of Water Resources in The Sultanate of Oman.

Data Analysis

Once all the data was input to arc/info files analysis and investigation were carried out. Spatial water quality distribution was assessed in conjunction with well depth and location. The relationship between spatial water quality and site specific water quality was investigated by querying the relational database. Overlays of water quality contours and hydrologic characteristics were carried through ARC/INFO and the results displayed on screen. Simulation modelling and quantification of specific variables for input into a Multi Attribute Tradeoff System (MATS) package were carried out to evaluate alternative water sources, various ground water recharge schemes and "preferred" decisions to effect policies. Appropriate hydrologic modelling can be accomplished from the data available in the regional database.

CHAPTER VI

RESULTS

The purpose of this study was to design a decision support system that would demonstrate how water resources management and planning policies can be implemented and supported in the Sultanate of Oman.

Central to this design was the organization of all water resources related data into a retrievable format. An extensive search of the Ministry of Water Resources (MWR) library was carried out to review previous consultants reports of the study area. It was found that although many studies have been conducted on the Batinah area and much "data" was collected, none of the reports concentrated exclusively on the south eastern Batinah area. The reports were not found to direct their objectives toward solving the water resources management and planning problems of the area, but rather to provide additional background information that would support future water resources exploration. The central focus of this study was the synthesis and organization of information to provide a rationale that would support policies directed at addressing the water resources management and planning issues of the study area.

Field data was collected from 47 monitoring wells that were located in the study area, this included well characteristics, type and use. The monitoring wells were owned and operated by Ministry of Agriculture and Fisheries, Ministry of Electricity and Water and Ministry of Water Resources (MWR). Data was collected from the records at the Seeb district offices of the MWR. Wells were identified by the identification number that is used by MWR for all monitoring wells. The Magellan Nav Pro 1000™ global position instrument (GPS) was used to verify location of the wells in UTM coordinates. Water level and water quality data for the period 1976-1990 were read from spreadsheet files at the Seeb district office. Further water level and water quality samples were recorded and analyzed for January and February 1991.

Database Organization

The database software that was chosen to serve as the central database for the decision support system was dBASE IV™. All field data collected was classified according to the design schema presented in Figure 12. Six database files were populated according to the following characteristics:

FILE NAME	FIELDS	# OF RECORDS
1. Rain_Day	District name Year Month	24
2. Rain_Year	District name Year Month	24
3. Water_Level	Well number Water level (MASL) Date	1592
4. Water_Quality	Well number Lab number Specific conductance Total Dissolved Solids ph Chloride (mg/l) Date Sampled	25
5. Water_Sample	Lab number Total Alkalinity Bicarbonate Alk. Sulfate Fluoride Bromide Nitrate Nitrogen Nitrite Nitrogen Total phosphate Total hardness Calcium hardness Magnesium hardness Calcium Magnesium Sodium Potassium Boron Soluble Iron(micro grams/liter) Ion Balance (% error) Sodium Absorption Ratio Sodium Equivalent Ratio	25
6. Wells	Well number Easting Northing District name Depth Diameter Date drilled Use Type Well identification number	47

Once all database files were populated, queries were performed to extract data for ARC/INFO files. The queries linked different files according to the data requirements. The main queries yielded water level data for the years 1978 to 1990, and water quality data for December 1990. The query files were saved in ASCII format and imported to a word processing file. The files were then transferred as DOS text files and read into ARC/INFO.

Arc/Info Output

The Seeb quadrant map 1:100000 scale served as the base map for digitizing coverage features of the study area. Four main coverage features were digitized, these were:

1. Oman Coastline: This described the coastline of the study area and landward limits. The X and Y minimum and maximum coordinates for the study area were declared as:

   Easting X Max = 635000.000

   X Min = 602000.000

   Northing Y Max = 2623000.000

   Y Min = 2606000.000

2. Oman Roads: Only tarmac roads were included in this coverage.
3. Oman Airport: The Seeb (International) airport was the main feature of this coverage.

4. Oman Wells: ALl 47 wells were described as label points according to their Easting and Northing and ID number.

Overlays of the Oman Coastline, Oman Roads and Oman Airport files in arcplot produced a comprehensive coverage that described the study area (Figure 13). Overlay of the Oman Coastline and Oman Wells files produced a coverage that illustrated the well locations in the study area (Figure 14).

Triangular Integrated Network commands were used to generate contours and isoplaths from the data imported from the database query files. Arctin commands were used to create smoothed contours at regular intervals of one meter, for the water level contours, and 5000 mg/l for the water quality isoplaths. Two regional water quality isoplaths were produced describing the Chloride levels (mg/l) and specific conductance levels (micromhos/cm) for December 1990. By using the Oman Coastline coverage as the transform file, contour files for each time period (June 1978-December 1990) were overlayed as background coverage in arcedit.

Once the coverage was viewed and analyzed for temporal and spatial trends in water quality and water levels, lattice commands were used to produce the final color coded contour and isoplath coverage in arcplot. Regional water level contours for the period June 1978 to December 1990 are described in Figures 15 to Figure 19.

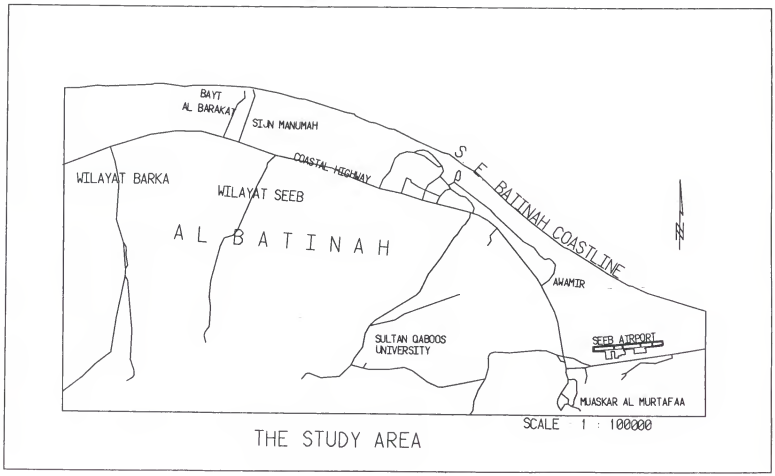

Figure 13. Digitized Coverage of the Study Area

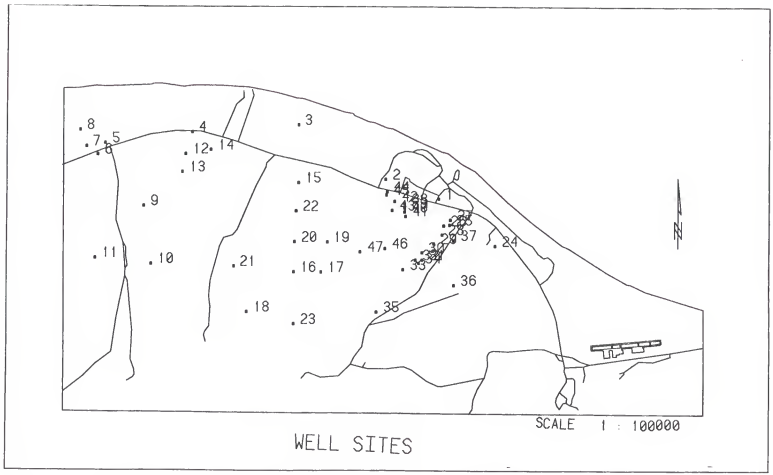

Figure 14. Digitized Coverage of Monitoring Well Location

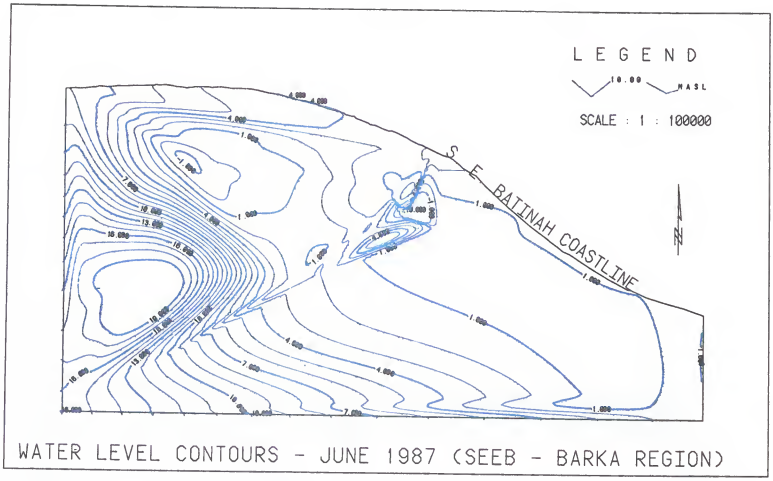

Figure 15. Water Level Contours for June 1987

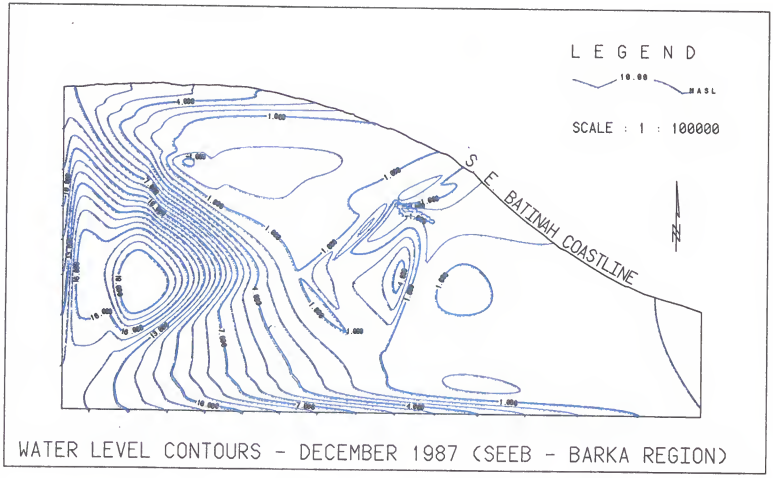

Figure 16. Water Level Contours for December 1987

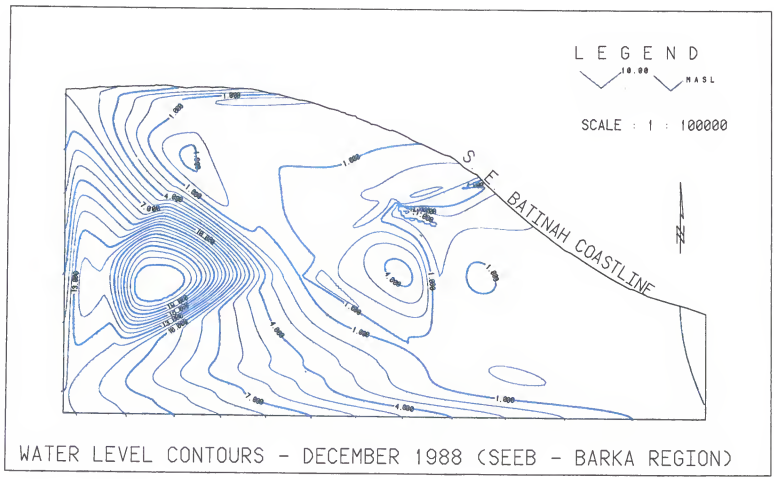

Figure 17. Water Level Contours for December 1988

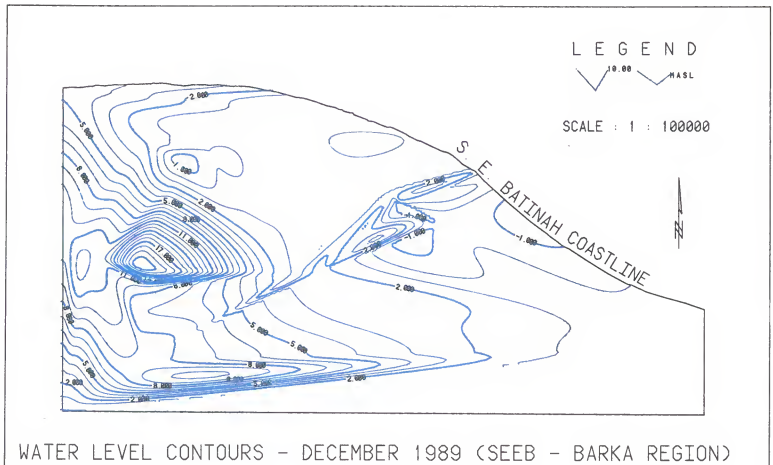

Figure 18. Water Level Contours for December 1989

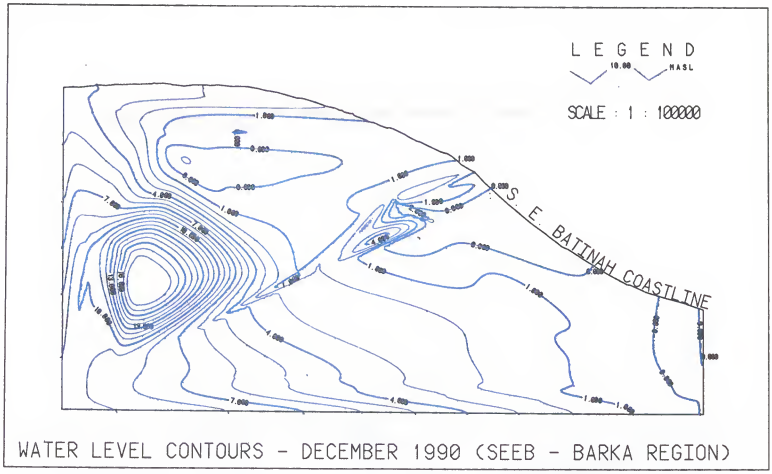

Figure 19. Water Level Contours for December 1990

Regional water quality isoplaths are described in Figure 20 (chlorides) and Figure 21 (specific conductance).

Satellite Data

Landsat TM (Thematic Mapper) digital data were processed on the ERDAS image processing system. The scenes were of quadrant one and two of a whole scene and scanned the area on January 28th, 1987.

Bands 1(Blue), 2(Green), and 4(Near-infrared) were chosen for processing. Band 1 is designed for water body penetration, and is used for coastal water mapping. It is also useful for soil and vegetation discrimination and cultural feature identification. Band 2 is designed for vegetation discrimination and evaluation of vegetation vigor. Band 2 is also useful for cultural feature identification. Band 4 is useful for determining vegetation types, vigor, and biomass content. It is also useful for delineating water bodies and for soil moisture discrimination. Histogram equalization was performed for image enhancement.

It was found that quadrant two was sufficient to cover the study area. The scene included the Muscat capital area and surrounding suburbs. Hard copies of the processed image showing the central features of the study area were made directly from the screen using a 35 mm camera and are shown in Figure 22 to 27. A 36" x 36" hard copy of quadrant two was also acquired from EARTHSAT CORP.

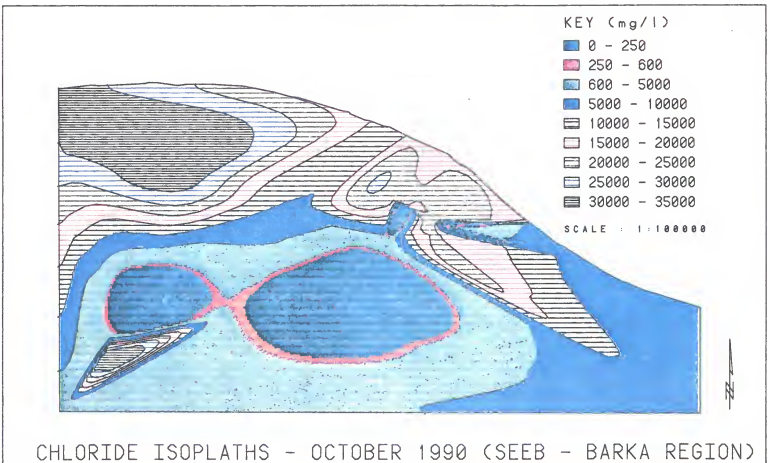

Figure 20. Regional Water Quality (Chlorides) December 1990

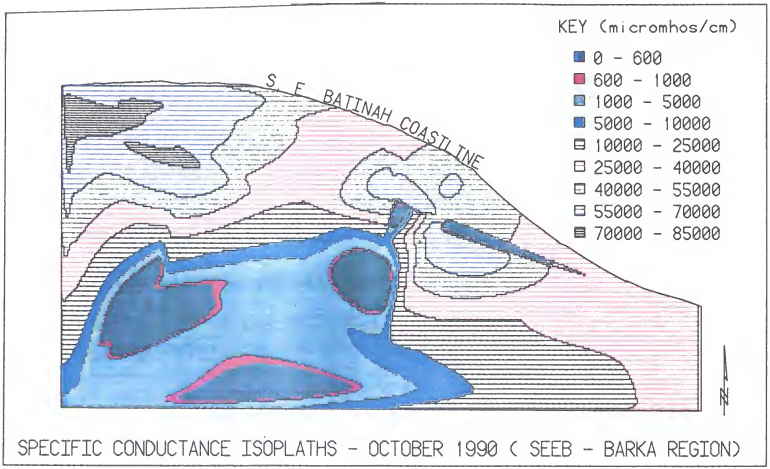

Figure 21. Regional Water Quality (Specific Conductance) December 1990

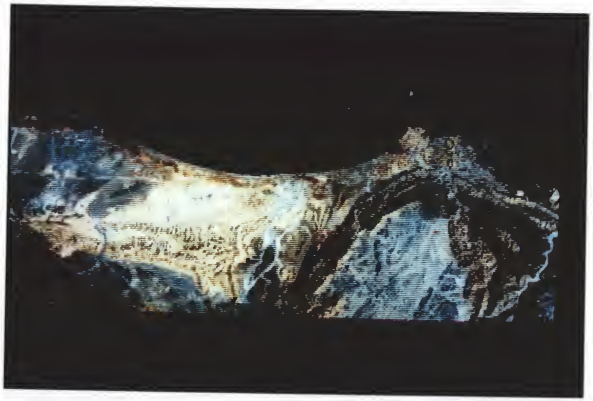

Figure 22. Processed TM Image Showing Northern Oman Coastline

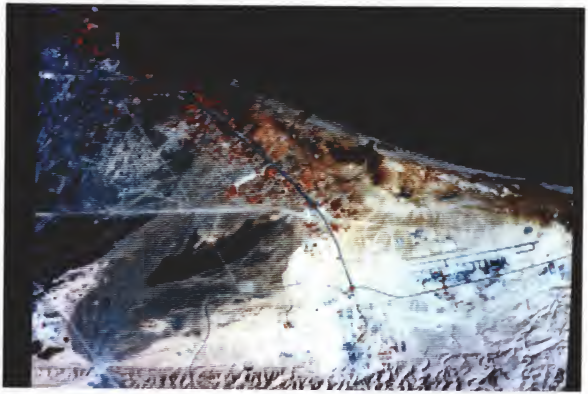

Figure 23. Processed TM Image Showing Seeb International Airport

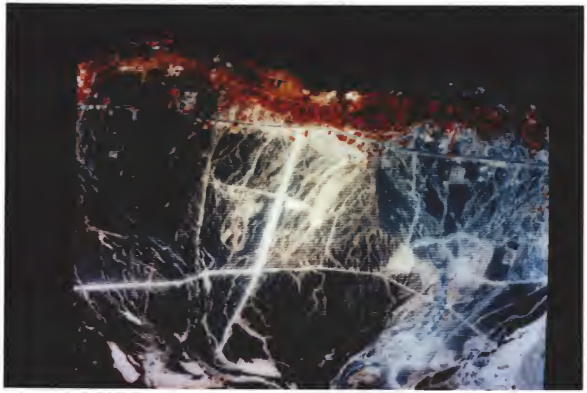

Figure 24. Processed TM Image Showing Batinah Coastline

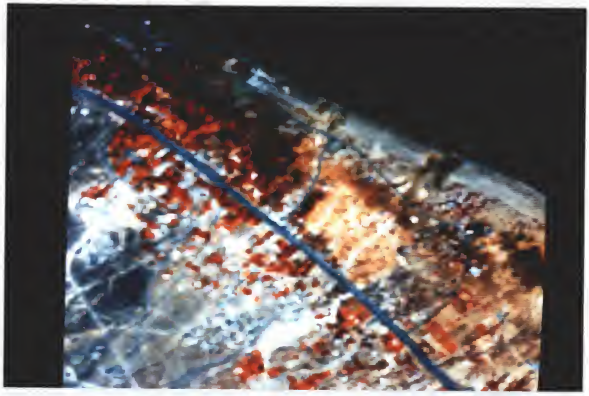

Figure 25. Processed TM Image Showing Zoom of Al Hayl Area

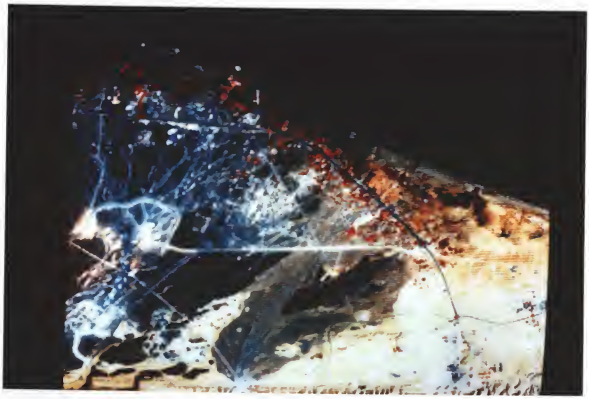

Figure 26. Processed TM Image showing the Study Area

Figure 27. Processed TM Image Showing Al Khawd Recharge Dam

The spectral resolution of 30 meters was found to be sufficient to identify cultural features of the area and general development trends. Land use patterns and development were identified and agricultural development patterns were clearly delineated.

MATS - Design and Output

A comprehensive analysis of the ArcInfo output was conducted to determine the state of the ground water resources of the study area. Temporal variation of the water levels revealed ground water levels fell rapidly over the period June 1987 to December 1990. Spatial evaluation of the water levels showed that the water levels increased landward with the lowest water levels being recorded along the coastal plain. The water quality isoplaths exhibited similar trends, with water quality increasing landward. Analysis of the satellite data revealed that the eastern section of the study area was experiencing greater residential development and commercial development than the western section which remains to be dominated by agricultural development. The agricultural development trend landward across the coastal highway reflects the activities of government policies which are designed to encourage private sector involvement in agricultural development.

Collectively the information from the database queries, ArcInfo output and satellite data, provided the

framework for designing two MATS runs. The MATS sessions were run to evaluate policy alternatives that were available to water resources decision makers for the area. The following section describes the factors and plans that were formulated for each run and the rational for quantification of the variables associated with each factor and plan.

1. "A Water Resources Recharge/Conservation Scheme for Oman".

PLANS	FACTORS
(1) Cap all wells	Yield (million gallons/year)
(2) Permit all wells	Use
(3) Well Injection	Capital cost ($ U.S.)
(4) Meter all wells	Annual coat ($ U.S.)
(5) Grey water	Lifetime (years)
(6) No action	Future worth (unitless)
	Acceptance (unitless)
	Dependency (unitless)

Definition of Plans:

(1) Cap all wells - This plan would be coordinated by the MWR after according to the well registration program. All privately owned wells would be capped and a moratorium on new drilling would be issued as a Ministerial decree.

(2) Permit all wells - This plan would issue well permits (consumptive use) for all private wells. The permits would be valid for five years and would be renewed only after review of the water resources planning board at MWR.

(3) Well injection - An aquifer recharge and recovery program would be designed. Desalinated water would be the primary source for this program. The injection well design and location would be determined according to the hydrogeology of the area to serve as a future source of water and provide additional benefits of increasing the salt water fresh water interface along the coast line.

(4) Meter all wells - All private wells would be metered. Initially no limits would be placed on consumptive use, however the metering program could potentially be use in conduction with the well permit program to control and possibly provide a framework for consumptive use charges according to current Ministry of Electricity and Water consumer charges.

(5) Grey water - A municipal sewage treatment facility would be designed to service the study area. All supportive distribution networks would also be designed to allow each consumer to use "free" tertiary treated effluent for irrigation an agriculture.

(6) No action - Everything would remain as it is. This plan is included because it provides a baseline for comparing the alternative actions.

Assumptions that were included about the community being served in this area were:

- All domestic users of ground water are "hobby farmers". Main use of the water is for gardens and recreation i.e. swimming pools.

- It is approximated that there are 1500 wells in the study area, and that each consumer uses 500 gallons per day. The cost of desalinated water is based on current MEW charges which is, $5.15/1000 gallons. That the quality of water conserved/recharged drinking water quality (250mg/l chloride). The rational for quantifying the impact of each plan on a factor was:

(1) Factor = YIELD

The impact of plan 1 (Capping all wells) on yield -:
There are 1500 wells pumping 500 gallons per day.

Thus: $1500 \times 500 \times 365 = 273.75 \times 10^6$ gallons/yr.

The impact of plan 2 (Permit all wells) -:
By implementing this plan it was concluded that there will not be a significant impact on the quantity of water that was pumped because the permits would serve as a confirmation to owners of the wells for their right to use the water. However because the permits are valid for five years it can be assumed that the owners will get an indirect "feeling" that they are being monitored. This is assumed to result in a more "conservative" pattern of the water used and may thus have an impact of reducing the overall, consumption and thus conserving, 10% of total yield.

Thus: 10% x (273.75 x 10^6)gallons/yr = 27.37 x 10^6 gallon/yr. The impact of plan 3 (Well injection) -: Assume we inject 1% of total desalinated water produced. Current total production from the Al Ghubra desalination plan is 21 MGD.

Thus: 1% x (21 x 10^6 gallons/day) x 365 = 7.66 x 10^6 gallons/yr. The impact of plan 4 (Meter all wells) -: This plan is very closely related to plan 3 (Permit all wells). However, metering the wells will definitely cause the owners aware (afraid) of being monitored so that it can be assumed that this plan will cause the owners to use less water. No restrictions are attached with the metering plan, all this plan is doing is providing a more rigorous monitoring program that could potentially have future benefits, e.g. better insight in water use patterns and quantity consumed. Given these considerations it was concluded that this plan would result in a 25% reduction of total water used.

Thus: 25% x (273.75 x 10^6)gallons/yr = 68.43 x 10^6 gallons/yr. The impact of plan 5 (Grey water) -: Providing "grey water" or effluent for gardening. With this plan the alternative water can only be used for irrigation and not for recreation purposes (such as swimming pools) and it cannot be use for domestic consumption either. It was assumed that the public would accept the concept of using treated effluent. This is a valid assumption because there is currently a grey water

program serving the residential complex at the Khoula hospital in town. Ground water would still be needed to meet other demands. Since the grey water will be provided free of charge to all consumers, the only charge to the consumer would be a hook up charge as is currently the practice for mains water hook up (the current hook up charge is $500.00 U.S.). It is therefore assumed that there will be a 60% reduction in ground water used.

Thus: 60% x (273.75×10^6) gallons /yr = 164.25×10^6 gallons/yr. The impact of plan 6 (No action) -:
This plan will leave things as they are. It was included to provide a baseline for the overall evaluation process. Current public awareness programs for conservation and physical hydrologic limitation would be the only impact on yield. It was concluded therefore that this plan would decrease production by 10% .

Thus: 10% x (273.75×10^6 gallons/yr = 27.37×10^6 gallons/yr.

(2) Factor = USE

For this factor a unitless valued scale was designed. The score is valued according to discriminating priorities which reflect traditional Islamic water laws and cultural habits and customs governing water use. A scale measured from 1-43 was calculated to measure the use that the conserved/recharged water would be put to. The score for each use was measured as follows:

43 = top possible score i.e. best use

1 = lowest score i.e. worst use

The uses were measured as:

1. Drinking = 10
2. Agriculture = 5
3. Domestic = 6
4. Garden = 4
5. Recreation = 1
6. Combat saline intrusion = 8
7. Reserved for strategic supply = 9

Thus the maximum points that a use could earn was 43.

The impact of plan 1 (Cap all wells) on the use factor -:

If this plan was implemented the water could be use for:

1. Combat saline intrusion = 8
2. Strategic reserve = 9
3. Drinking water = 10

TOTAL = 27

The impact of plan 2 (Permit all wells) on use -:

It was previously calculated that this plan would conserve/recharge 10% of total water consumed = 27.37 x 10^6 gallons/yr. Thus all water conserved/recharged will be used for:

Drinking = 10

TOTAL = 10

The impact of plan 3 (Well injection) on use -:

All water will be used for:

1. Combat saline intrusion = 8

2. Strategic reserves = 9

TOTAL = 17

The impact of plan 4 (Meter all wells) on use -:

All water conserved will be used for:

1. Drinking water = 10

2. Saline intrusion = 8

TOTAL = 18

The impact of plan 5 (Grey water) on use -:

All water conserved will be used for:

1. Agriculture = 5

2. Strategic reserves = 9

3. Combat intrusion = 8

4. Gardens = 4

TOTAL = 26

The impact of plan 6 (No action) on use -:

The situation remains the same and water use is as it is now:

1. Drinking = 10

2. Agriculture = 5

3. Domestic = 6

4. Gardens = 4

5. Recreation = 1

TOTAL = 26

(3) Factor = CAPITAL COST

The impact of plan 1 (Cap all wells) on capital cost -:

Materials = \$250.00/well x 1500 wells = \$0.375 $x10^6$

Labor = \$60.00/well .. = \$0.090 $x10^6$

Inventory = \$25.00/well .. = \$0.038 $x10^6$

TOTAL CAPITAL COST FOR PLAN = \$0.503 $x10^6$

The impact of plan 2 (Permit all wells) on capital cost -:

This cost for this plan will include administrative costs i.e. man-hours plus the public announcements to notify public of new law. Thus:

Salary of administrator in civil service = \$1550/month

Works 40 hrs/week and 160 hrs/month

Thus: 1550/160 = \$9.68/hr (round off to \$10.00) The plan would need eight men and would take three months to complete the job.

Thus: TOTAL CAPITAL COST FOR PLAN = \$0.058 X 10^6

The impact of plan 3 (Well injection) on capital cost -:

It was concluded that 1% of total desalinated water produced would set aside for the well injection program, thus:

1% x [(21 x 10^6 gallons/day) x 365 gallon/yr] = 7.665 x 10^4 gal/yr

Desalinated water costs are \$5.15/1000 gallons,.

Thus: (7.66 x 10^6/1000) x \$5.15 = \$0.395 x 10^6 this is the water cost alone. Engineering cost for the project was included as 35% of total water cost, thus = \$0.138 x 10^6

The total cost is: \$0.138 x 10^6 + 0.395 x 10^6 = \$0.533 x 10^6

Thus: TOTAL COST OF PLAN = $0.533 X 10^6

The impact of plan 4 (Meter all wells) on capital cost -:

Meter connection would cost $129.00 per well.

Thus: $129.00 x 1500 = $0.194.00 x$10^6$

TOTAL COST OF PLAN = $0.194.00 X 10^6

The impact of plan 5 (Grey water) on capital cost -:

Since there is currently no central sewage treatment plant that services this area,the cost of building a new sewage treatment plant with a treatment capacity of 1-2 million gallons per day, plus all supply networks would be the total cost.

Thus: TOTAL COST OF THE PLAN = $20 X 10^6

The impact of plan 6 (No action) on the capital cost -:

This plan would require that the current monitoring well program be maintained and the current research and development cost for the area.

Thus: TOTAL COST OF THE PLAN = $0.03 X 10^6

(4) Factor = ANNUAL COST

The impact of plan 1 (Cap all wells) on annual cost -:

The annual cost would be the labor charge for maintenance and monitoring, which is calculated as $60.00/well/year.

Thus: TOTAL ANNUAL COST FOR PLAN = $0.09 X 10^6

The impact of plan 2 (Permit all wells) on annual cost -:

Permits would be valid for five years. The annual cost would be a fifth of capital cost.

Thus: TOTAL ANNUAL COST OF THE PLAN = $0.012 X 10^6/yr. The impact of plan 3 (Well injection) on annual cost -:

According to Kimrey (1989), well injection programs require frequent and continuous maintenance which can total up to 10% of the capital cost.

Thus: TOTAL COST OF THE PLAN = $0.053 X 10^6

The impact of plan 4 (Meter all wells) on annual cost -: The only annual cost would be the reading and maintenance of the meters.

Thus: TOTAL COST OF THE PLAN = $0.045 X 10^6

The impact of plan 5 (Grey water) on annual cost -: Since there will be no charge to the consumer for the use of grey water the total cost must be carried by the government. The maintenance and supply would be 5% of capital cost.

Thus: TOTAL COST OF THE PLAN = $0.10 X 10^6

The impact of plan 6 (No action) on annual cost -: The cost of maintaining the monitoring well program and research and development would be the same as capital cost.

Thus: TOTAL COST OF THE PLAN = $0.03 X 10^6

(5) Factor = LIFETIME

The lifetime of the all projects is designed to be 20 years. Thus all impacts for this factor would be the same at 20 years, accept for the plan of No Action. It is concluded that if current rates of development persist the

area would be depleted of recoverable ground water in five years. Thus the lifetime for this plan is 5 years.

(6) Factor = FUTURE WORTH

This was a subjective factor which dealt with the "value" in terms of customs, habits and laws of the community and their values regarding the ground water resources, the future impact of each plan in terms of the social, ethical and political context of the community; the future worth of preserving the ground water resources for future generations; and the impact of capping wells on the quality of life of the community as a whole. A scale from 1 - 10 was devised to measure this future worth. One represented "poor" future worth and 10 "best" future worth. Each score that was assigned was a result of the synthesis (by the decision maker) of the subjective variables that are significant for each plan.

(7) Factor = ACCEPTANCE

A scale from 1 - 10 was designed to measure the acceptance of each plan by the public. The Omani public tend to be obedient to authority; however, plans that infringe on rights that are traditionally considered fundamental to tenants of religion can and are opposed and receive little acceptance. In this scale 1 represents the least accepted plan and 10 the most accepted plan.

(8) Factor = DEPENDENCY

This factor measures how dependable the plan is to provide the desired results. Again, a synthesis of the decision

maker's knowledge and experience was required to assign the relative scores. A score of 1 represented the least dependability of the plan and a score of 10 represented the maximum dependability of the plan to produce the desired results.

Table 4 summarizes the impacts of the factors on each plan for the recharge/conservation scheme. Weights were assigned to each factor according to the values of the decision maker. Figure 28 represents the assigned weights for each factor (for recharge/conservation) and overall scores for each plan are represented in Figure 29.

Since a plan corresponding to the current conditions represents the condition that will exist if no other plan was implemented or chosen (i.e. No Action), an assessment of the absolute value of the plans can be made. That is it can be said that "Capping all wells" represents an improvement over the current condition and the other plans represent decreasing desirability according to their scores.

Sensitivity analysis for the first run of the evaluation of a recharge/conservation schemes for the area was carried out. The first sensitivity analysis varied the weights assigned to capital cost and yield, the second sensitivity analysis varied the weights assigned to capital cost and annual cost. Figure 30-33 represents the weights and factors, respectively, for the recharge/ conservation scheme sensitivity analysis.

Table 4. Impact Matrix for MATS Recharge/Conservation Scheme

FACTOR	P	L	A	N		
	CAP ALL WELLS	PERMIT ALL WELLS	WELL INJECTION	METER ALL WELLS	GREY WATER	NO ACTION
YIELD (CAL)	273.75*10^6	27.37*10^6	7.66*10^6	68.43*10^6	164.25*10^6	27.37*10^6
USE*	27	10	17	18	26	26
CAPITAL COST($)	0.503*10^6	0.058*10^6	0.533*10^6	0.194*10^6	20.00*10^6	0.03*10^6
ANNUAL COST($)	0.09*10^6	0.012*10^6	0.053*10^6	0.045*10^6	0.10*10^6	0.03*10^6
LIFETIME(YRS)	20	20	20	20	20	5
FUTURE WORTH*	8	5	6	9	10	1
ACCEPTANCE*	1	6	10	3	8	9
DEPENDENCY*	5	4	8	7	10	1

* Measured on a unitless (valued) scale

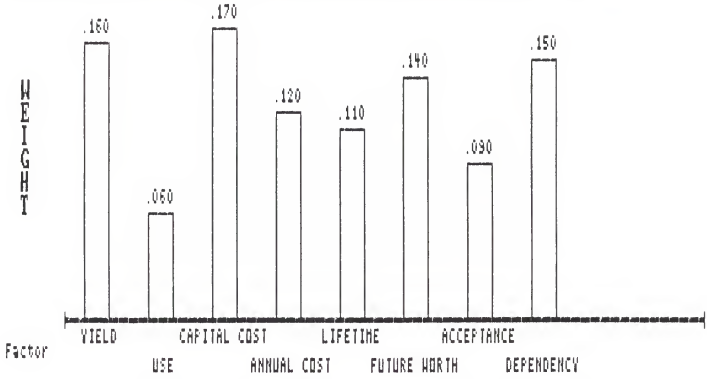

Figure 28. Weights for the Recharge/Conservation Scheme

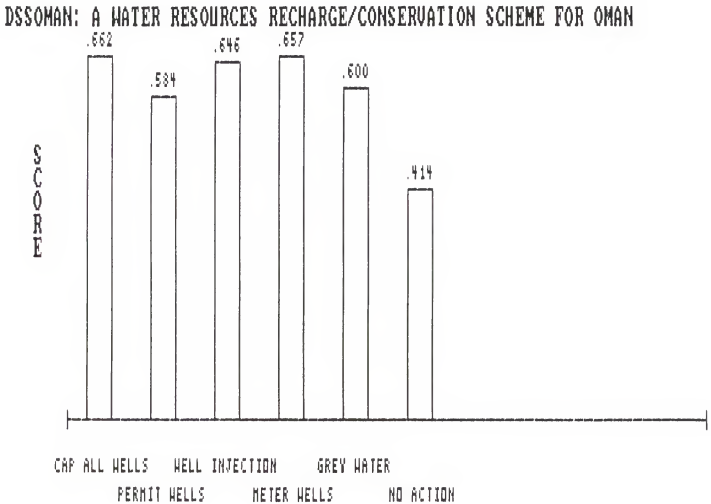

Figure 29. Overall Score for Recharge/Conservation Scheme

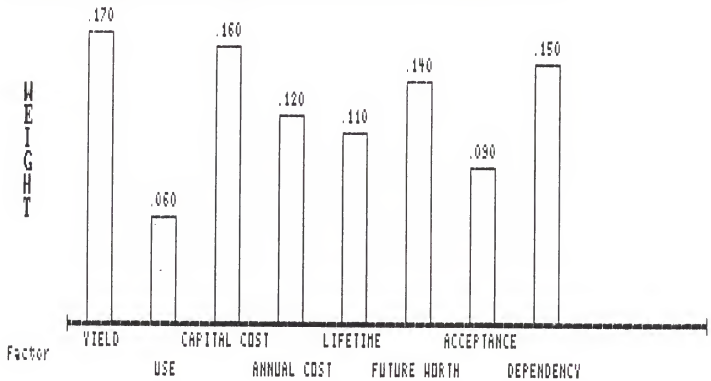

Figure 30. Weights for Sensitivity Analysis (Recharge/Conservation)

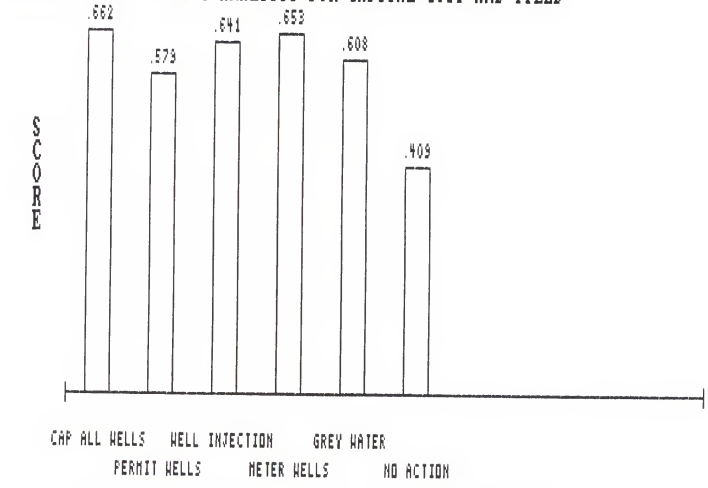

Figure 31. Overall Score for Sensitivity Analysis (Recharge/Conservation)

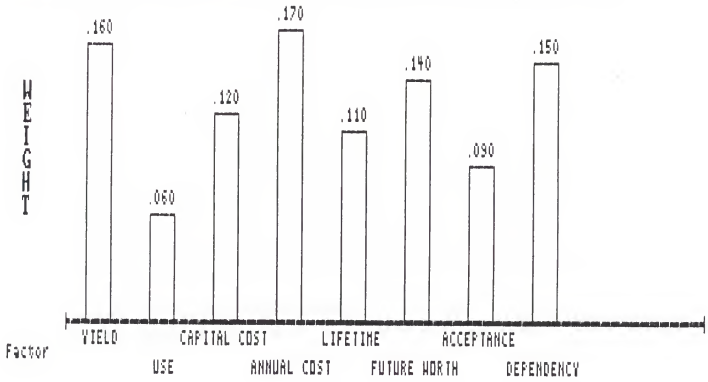

Figure 32. Weights for Sensitivity Analysis (Recharge/Conservation)

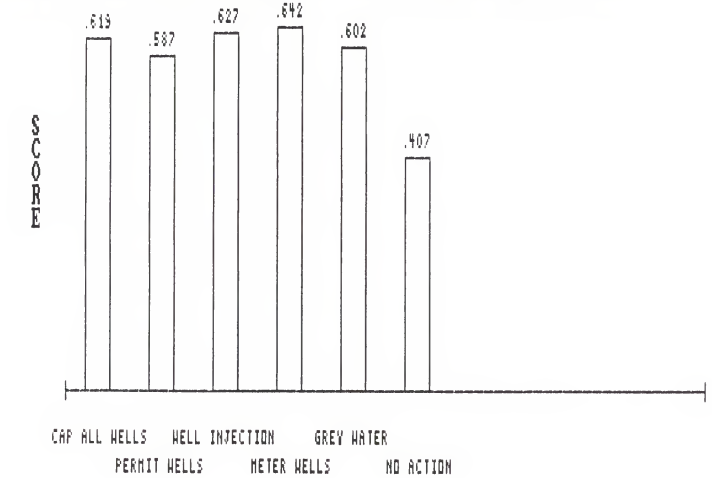

Figure 33. Overall Score for Sensitivity Analysis (Recharge/Conservation)

Evaluation of potential water supply sources was carried out a second MATS run. Seven plans and ten factors were assessed to determine the preferred plan. These were described as:

(2) "Evaluation of Potential Water Supply Sources for Oman".

PLANS	FACTORS
Wadi Mayh	Yield
Batinah	Capital cost
Wadi Dayqah	Annual cost
Wadi Khawd	Quality
Desalination (1 unit)	Distance from grid
Desalination (2 units)	Use
Desalination (3 units)	Lifetime
	Impact
	Dependency
	Future worth

The plans represented the various sources that could be exploited to service the growing demand for potable water. All water sources were assumed to yield water of drinking water standard (250 mg/l Chlorides). The rational for scoring the impacts for each factor were maintained as for the first MATS run. Two additional factors were assessed in the second run, these were Quality and Distance from the grid. The distance from the grid describes the distance in kilometers of the source from mains water supply grid. The greater the distance the less desirable is the source. As determined earlier all sources had to yield water that was of drinking water standard. The impact matrix for the second MATS run is described in Table 5. Figure 34 represents the weights and Figure 35

Table 5. Impact Matrix for MATS Water Supply Source Scheme

F A C T O R		P	L	A	N		
	WADI MAYH	BATINAH	WADI DAYQAH	WADI KHAWD	DESAL' 1 UNIT	DESAL' 2 UNITS	DESAL' 3 UNITS
YIELD (GAL)	1.45*10^6	6.6*10^6	9.5*10^6	2.89*10^6	3.69*10^6	4.96*10^6	6.3*10^6
CAPITAL COST($)	4.92*10^6	67.2*10^6	83.0*10^6	18.0*10^6	21.6*10^6	24.1*10^6	33.6*10^6
ANNUAL COST($)	191*10^3	1798*10^3	2430*10^3	30*10^3	3005*10^3	4014*10^6	4720*10^3
QUALITY(Cl mg/l)	250	250	250	250	250	250	250
DISTANCE(km)	5	150	90	15	1	1	1
USE*	10	9	10	10	8	8	8
LIFETIME(YRS)	20	10	15	20	15	20	30
IMPACT*	2	9	1	3	8	9	10
DEPENDENCY*	8	1	10	5	6	5	4
FUTURE WORTH*	5	1	5	10	8	8	8

*Measured on a unitless (valued) scale

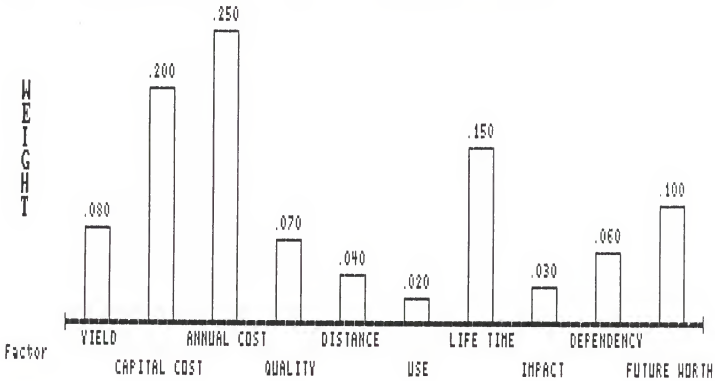

Figure 34. Weights for Water Supply Scheme

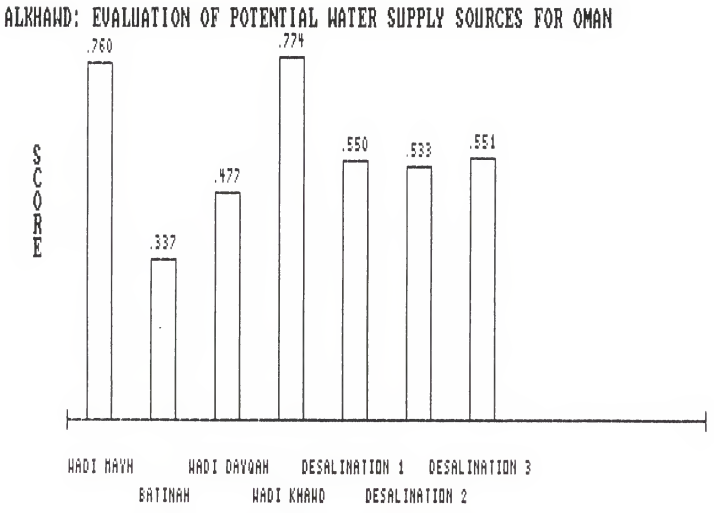

Figure 35. Overall Score for Water Supply Scheme

the overall scores. Sensitivity analysis was carried out by varying the weights for capital cost and yield. Figure 36 represents the weights for the sensitivity analysis and the results for the run are described in Figure 37.

Varying the weights for capital cost, yield and annual cost was found to be the most valid representation of the decision makers' concerns. Currently capital costs are the main concerns of most development projects in Oman. Working within their assigned budgets is the greatest challenge for all government ministries in Oman. The annual cost of maintaining the plans that are implemented is a critical factor in long term planning. Sustainable development is the key issue that must be considered. In the context of water resources projects, the amount of water that is produced (yield) is a major influence in providing the incentive to implement a plan. Thus the three factors whose weights were varied in the sensitivity analysis are representative of the critical concerns to the decision maker.

MATS-PC output includes a comprehensive listing of tables that represent the results throughout the evaluation process. The complete output for the evaluation process for all the MATS runs is contained in Appendix A.

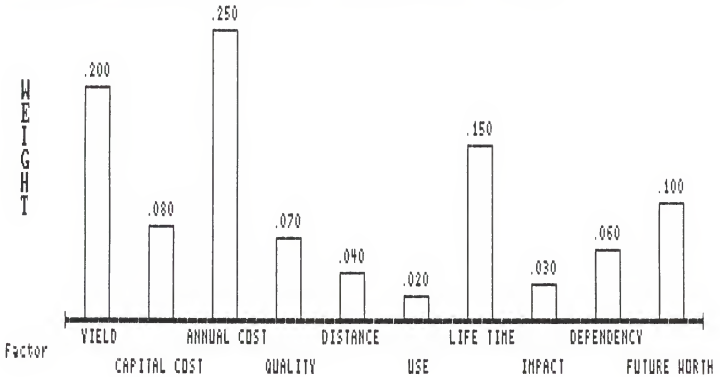

Figure 36. Weights for Sensitivity Analysis (Water Supply) Scheme

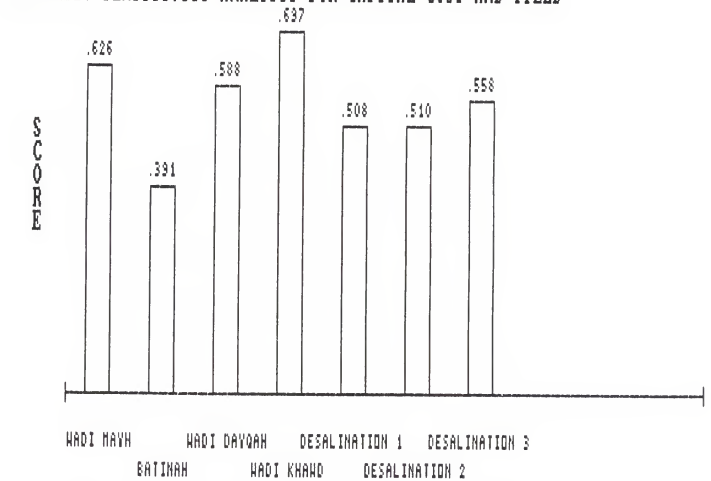

Figure 37. Overall Score for Sensitivity Analysis (Water Supply) Scheme

CHAPTER VII

DISCUSSION

The purpose of this study was to demonstrate how the use of a decision support system could result in formulation and implementation of water resources management and planning policies in the Sultanate of Oman. Four central components were incorporated into the decision support system. These were; a database management system, a geographical information system, satellite data, and a multicriteria decision analyses model. The synthesis of information using these four central components to support water resources management and planning policies in the Sultanate of Oman is described as follows:

The relational database design that was used in this study permits the relevant water resources data to be stored and organized in a retrievable format. As additional data are collected, files can be expanded and updated. Although water rights and institutional data were not included in the current database due to time and manpower constraints, an additional catalogue can be created which contains the laws, rules and regulations describing the institutional structure and water rights of

the community. Updating files is a simple task that can be carried out by regional office staff. A network of the database can be designed to connect all regional offices and allow water management officers in different regions to have access to the information contained in the central database. Answers to queries are instant and accurate, producing consistency in results and reducing duplication of efforts within the ministry. Cooperation and exchange of information between ministries can also be greatly facilitated by the database. Consultants who are employed by one ministry can easily access information that has already been collected by other ministries thus reducing the cost and time associated with completion of the projects. Historical data will support efforts to monitor future trends in rainfall and hydrologic conditions as well as institutional changes. The database ensures that results of water assessment and monitoring projects are properly organized and stored in a consistent format. The organization of the data collected in the last two decades of water resources projects in Oman is a first (and crucial) step towards affecting policies that reflect the realistic constraints of the water resources of the country.

The use of GIS systems to support water resources management and planning in Oman is particularly useful. The graphics output that is produced presents the results in a clear and readable format. It is not unique to Oman

that upper level managers and decision makers are not trained in the technical fields they manage, therefore a well presented color graphics output can obviate the need for highly trained technical "experts" to interpret results for managers. The water level contours that were produced in this study are easy to read and show the trends of falling water levels in a clear and readable format. Color coded isoplaths describing regional water quality can alert the manager to critical zones and provide a spatial concept of the area involved in relation to other known areas or districts. Digitized coverage allows overlays to be made that present different scenarios. The coverage can be as detailed as the information permits or the extraneous information can be omitted to allow a clearer representation of the concepts being illustrated. In the current study the evaluation of recharge efficacy of the Al Khawd recharge dam can be made by analyzing the changes in value of the water level contours. The results showed that in June 1987 the highest water level was 19m located south each of the catchment area of the dam. After the rains, which averaged 62mm for the months of February through April in 1987-1988, the highest water level recorded was 22m in the same area as the previous record. The water manager can conclude, with a relative degree of confidence, that recharge of the aquifer was greatest around the Al Khawd dam area thus providing a quantitative measure for

evaluating the efficacy of recharge provided by the dam. Water quality isoplaths for December 1990 show that the highest water quality is concentrated around the area of the recharge dam, confirming that significant recharge is being experienced in this area. Continuous monitoring of the area can provide information that would either support the construction of recharge dams in other areas or evaluate alternative methods of enhancing recharge. "What if" scenarios can be performed to simulate the effect of future projected withdrawals based on current practices, further projected rainfall data can be input to measure the impact on water levels and quality of the area.

The dynamic nature of the GIS-ArcInfo software offers few limitations as to applications that can be made given sufficient data. The graphics output provides a basis for decision makers involved in evaluating the results and formulating policies that can be supported with visual data.

Satellite data can be processed to enhance different features according to the user's preference. The areal coverage that is attained permits an evaluation of resources and cultural features within a single scene. The Landsat TM image that was processed in this study revealed distinct cultural features that enhance the value of the water level contours and regional water quality isoplaths. The image showed that there is intensive agricultural activity concentrated between the coastal

highway and the coastline. This area was also found to have the lowest water levels and water quality. Moving westward from the airport the land use patterns show a trend from residential to agriculture. This is due to the rapid degradation of the water quality along the eastern part of the study area which forced the owners to abandon their farming practices and sell the land for residential development. It can be seen (Figure 27, showing the Al Khawd area) that residential areas are also being developed in the area east of the Al Khawd am. A university and industrial complex have also been developed in the same area. A rigorous evaluation of the zoning laws can be performed to determine the impact of these development activities on the ground water resources of the area.

Agriculture dominates the western portions of the study area and the trend of small parcels of agricultural development landward is clearly evident in these areas. Careful analysis of the satellite data can delineate large catchment basins and potential flood zones. This information could be used to design future ground water recharge structures and large scale agricultural projects. Georectification of satellite data can allow the direct integration of real time data from ArcInfo coverage with satellite data, this would add a powerful dimension to the evaluation and decision making process.

The MATS-PC multi criteria decision making model that was used in this study was well suited to the holistic approach to water resources management and planning. The objective of any information processing is the formulation and implementation of a policy or decision. Two policy analyses were performed in this study using the MATS-PC. Six plans and eight factors were included in the first analysis to determine the preferred solution to designing a water resources and recharge/conservation scheme for the study area. The results showed that capping all wells in the area was the preferred plan. It is interesting to note that issuing well permits, which MWR is currently investing much of its energy and resources, was one of the least preferred plans next to taking no action at all. This is a prime example of how a comprehensive analysis of alternatives can provide insight into the policy arena. It should be noted however that a holistic approach to water policy analysis should not ignore the possibility of choosing and prioritizing a combination of several plans. Political and social realities must be acutely born in mind by the decision maker who must have the foresight to not wallow in the illusion that a MATS analysis is the panacea to the complex issue of water resources policy making. A more realistic compromise in the MATS evaluation would be to initially implement a well metering program and monitor the effects for a period of twelve months, if significant changes are found in the

consumptive use patterns a grey water program can be implemented. If no significant improvement in water levels and water quality are recorded a consumptive use permit system can be implemented. Close monitoring of the ground water resources should be maintained and as a last resort the well capping and well injection plans should be implemented simultaneously.

A sensitivity analysis which varies the weights assigned to capital cost and yield and capital cost and annual cost allow the decision maker to evaluate the impact of changing values (or priorities) which would reflect a developing economy which is dependent on crude oil exports that have been characterized by precipitous changes in the past. It was found that when the highest weight is assigned to yield instead of capital cost the preferred plan is still capping all wells followed by a metering program. When the annual cost is assigned the highest weight the preferred plan is found to be the well metering plan followed by well injection and capping all wells. This evaluation represents a more realistic approach to addressing the water resources recharge/conservation schemes for the area.

Evaluation of potential water supply sources for the area included seven plans and ten factors. The overall scores indicated that the Wadi Al Khawd basin, which is included in the study area, was the preferred source. The Batinah area, however was found to be the least preferred

choice as a potential source. This result is particularly significant when considered in the context of the governments plans to make the Batinah "the bread basket of Oman". It is clear that from this analysis that the rational for such a plan should be given serious consideration. This conclusion is confirmed by the projected water demands that have been calculated in the Water Resources Master Plan, which predicts that the Batihan area will have the highest population of any region in Oman by the year 2010. The sustainable development of the Batinah area should be seriously questioned under such a burgeoning population. A sensitivity analysis that assigned the greater weight on yield than the capital cost was found to maintain the preferred plan as Wadi Al Khawd and clearly demonstrated the economies of scale in the three plans for constructing a one, two or three unit desalination plant.

Implementing a new method for policy formulation in any setting involves a daunting series of tasks. The literature on implementation within the United States is replete with studies documenting implementation difficulties (White, 1990). The task is anticipated to be even more difficult for organizations in developing countries such as the Sultanate of Oman. In his comprehensive study on implementing policy reforms in lessor developed countries (LDCs) White (1990), reports that LDCs have hierarchial and centralized institutions

that thrive on routinized bureaucratic procedures and "going by the book" rather than problem solving. Typically the norms within LDC organizations discourage innovation, officials are not used to thinking of policy as a way to solve problems or of implementation in terms of performance. Oman is not immune to this phenomenon.

The challenge is to be able to transfer the decision support system that was designed in this study to users in Oman. Coordination of the development projects of the eighteen governmental agencies involved in water resources management and planning in the Sultanate of Oman is the first step towards transferring the DSS that was designed to users in Oman. This can be achieved by forming a Delphi panel whereby synthesis of ideas and objectives of the relevant agencies can be carried out. The objective would be to reach a consensus as to the institution that must be established in order to coordinate the activities of all agencies. A centralized approach towards water resources management and planning must be formulated in the initial stages to allow the central agency (MWR) to organize and distribute the DSS capabilities to the relevant agencies. Once this is established communication between each agency can be achieved without infringement of jurisdiction of the individual authority by another agency. The DSS will function as a tool that is there to help the managers formulate decisions and policies according to site specific criteria. Each agency can

update the data files as new data becomes available for their district. The MWR central offices can monitor water resources development activities throughout the Sultanate. This is particularly important for Oman because policies that need to be directed towards users in the urban areas differ greatly from policies that may be implemented by agencies in the rural districts where water use and development have different values and priorities. The DSS can reduce conflict that is often invoked by policies which are declared law for all users.

Fedra (1990), points out that in order to turn a potentially useful method into one actually used, a number of special features are required as well as an approach that takes psychological, institutional, scientific and technical aspects into account. Tools that are easy to use, use problem-adequate representation formats and a high degree of visualization, customized for an institution and its specific view of problems, and that are developed in close collaboration with the end user, have been found to stand a better chance of being used than tools that are based on "only" good science (Fedra, 1990). Good science is a necessary, but certainly not sufficient, condition for a useful and usable information and decision support system. It is further noted by Fedra, (1990), that information and decision support systems generally imply a change in personal work habits, institutional procedures, and thus, institutional culture.

While they may or may not change what is done, they most certainly change the way things are done - if they are used.

The decision support system that was designed in this study should be viewed in the context of the vast arena of the water resources planning and management strategies and the dynamics of a changing society. Oman has, and will not doubt continue to, undergo many changes in its institutional and social structure. The expectations and quality of life of the new generation of Omanis differ greatly from the older generation who had to survive and prosper within the constraints of limited water and natural resources. Like many other nations Oman must learn to maintain a balance that has provided many benefits for the people and their welfare. Omanis must not however be swept up by the illusion that the continued flow of crude oil can be readily exchanged for water.

Conclusion

The results of this study demonstrate how information can be processed through the use of appropriate technologies, to yield a framework for decision making. The decision support system that was designed in this study should not be viewed as a prosthesis, but rather a tool, or more accurately a tool box, that can assist the water resources manager to follow a more holistic strategy in formulating water resources management and planning

policies. The application of the DSS towards addressing the water resources issues of the study area has demonstrated that:

- The limited ground water resources of Oman cannot continue to support the current rates of withdrawal.

- Ground water quality is experiencing rapid degradation as a result of salt water intrusion caused by overpumping. This problem is particularly acute in the coastal agricultural area.

- The Al-Khawd recharge dam is providing ground water recharge for the area, however the recharged water is rapidly pumped from the ground.

- Alternatives to addressing the water resources problems of the area are available and a rational method for evaluating them is included in the DSS.

- Agricultural development must be located in areas where the ground water resources can support such development.

- Although implementation of the DSS may initially result in increasing the conflict between the different governmental agencies involved in water resources development, in the long run it will integrate the activities of the different agencies, prevent duplication of efforts, incite greater exchange of information and ideas between agencies and provide an efficient method for evaluating water resources development projects.

- The DSS can be used by all governmental agencies and adapt to the changing institutional setting.

APPENDIX

Project = DSSOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

FACTOR WEIGHTS

CAPITAL COST	0.170	THE CAPITAL COST OF THE PLAN (in MILLION DOLLARS)
YIELD	0.160	QUANTITY OF WATER PRODUCED ANNUALY (in MGY) BY THE PLAN
DEPENDENCY	0.150	THE DEPENDABILITY OF THE PLAN TO RECHARGE/CONSERVE WATER
FUTURE WORTH	0.140	THE FUTURE UTILITY (WORTH) OF THE PLAN (unitless)
ANNUAL COST	0.120	ANNUAL COST OF MAINTENANCE OF THE PLAN (in MILLION DOLLARS)
LIFETIME	0.110	THE EXPECTED LIFETIME (in YEARS) OF THE PLAN
ACCEPTANCE	0.090	THE ACCEPTABILITY OF THE PLAN BY THE PUBLIC (unitless)
USE	0.080	USE OF THE WATER FROM A CHOICE OF SEVEN (RATED) USES

Project = DSSOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

FUNCTION FORMS

YIELD QUANTITY OF WATER PRODUCED ANNUALY (in MGY) BY THE PLAN
Objective : 7.0 274.0
Subjective : 0.000 1.000
Weight = 0.160

USE USE OF THE WATER FROM A CHOICE OF SEVEN (RATED) USES
Objective : 1.0 43.0
Subjective : 0.000 1.000
Weight = 0.060

CAPITAL COST THE CAPITAL COST OF THE PLAN (in MILLION DOLLARS)
Objective : 0.0 20.0
Subjective : 1.000 0.000
Weight = 0.170

ANNUAL COST ANNUAL COST OF MAINTENANCE OF THE PLAN (in MILLION DOLLARS)
Objective : 0.0 0.1
Subjective : 1.000 0.000
Weight = 0.120

LIFETIME THE EXPECTED LIFETIME (in YEARS) OF THE PLAN
Objective : 1.0 20.0
Subjective : 0.000 1.000
Weight = 0.110

FUTURE WORTH THE FUTURE UTILITY (WORTH) OF THE PLAN (unitless)
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.140

ACCEPTANCE THE ACCEPTABILITY OF THE PLAN BY THE PUBLIC (unitless)
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.090

DEPENDENCY THE DEPENDABILITY OF THE PLAN TO RECHARGE/CONSERVE WATER
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.150

Project = DSSOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

PLAN EVALUATION

NO ACTION: DO NOT IMPLEMENT ANY POLICY FOR RECHARGE/CONSERVATION

Factors	Objective	Subjective	Weighted Subj.
YIELD	27.4	0.076	0.012
USE	26.0	0.595	0.036
CAPITAL COST	0.0	1.000	0.170
ANNUAL COST	0.0	0.778	0.093
LIFETIME	5.0	0.211	0.023
FUTURE WORTH	1.0	0.000	0.000
ACCEPTANCE	9.0	0.889	0.080
DEPENDENCY	1.0	0.000	0.000

TOTAL SCORE = 0.414

Project = DSSOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

PLAN EVALUATION

PERMIT WELLS: ISSUE FIVE YEAR CONSUMPTIVE USE PERMITS ON ALL WELLS

Factors	Objective	Subjective	Weighted Subj.
YIELD	27.4	0.076	0.012
USE	10.0	0.214	0.013
CAPITAL COST	0.1	0.999	0.170
ANNUAL COST	0.0	0.978	0.117
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	5.0	0.444	0.062
ACCEPTANCE	6.0	0.556	0.050
DEPENDENCY	4.0	0.333	0.050

TOTAL SCORE = 0.584

Project = DSSOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

PLAN EVALUATION

GREY WATER: DESIGN AND IMPLEMENT AN SEWAGE EFFLUENT REUSE PROGRAM

Factors	Objective	Subjective	Weighted Subj.
YIELD	164.2	0.589	0.094
USE	26.0	0.595	0.036
CAPITAL COST	20.0	0.000	0.000
ANNUAL COST	0.1	0.000	0.000
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	10.0	1.000	0.140
ACCEPTANCE	8.0	0.778	0.070
DEPENDENCY	10.0	1.000	0.150

TOTAL SCORE = 0.600

Project = DSSOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

PLAN EVALUATION

WELL INJECTION: DESIGN AN AQUIFER STORAGE AND RECOVERY PROGRAM

Factors	Objective	Subjective	Weighted Subj.
YIELD	7.7	0.002	0.000
USE	17.0	0.381	0.023
CAPITAL COST	0.5	0.975	0.166
ANNUAL COST	0.1	0.522	0.063
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	6.0	0.556	0.078
ACCEPTANCE	10.0	1.000	0.090
DEPENDENCY	8.0	0.778	0.117

TOTAL SCORE = 0.646

Project = DSSOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

PLAN EVALUATION

METER WELLS: INSTALL METERS ON ALL WELLS IN THE AREA

Factors	Objective	Subjective	Weighted Subj.
YIELD	68.4	0.230	0.037
USE	18.0	0.405	0.024
CAPITAL COST	0.2	0.992	0.169
ANNUAL COST	0.0	0.611	0.073
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	9.0	0.889	0.124
ACCEPTANCE	3.0	0.222	0.020
DEPENDENCY	7.0	0.667	0.100

TOTAL SCORE = 0.657

Project = DSSCMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

PLAN EVALUATION

CAP ALL WELLS: CAP ALL PRIVATELY OWNED WELLS IN THE AREA

Factors	Objective	Subjective	Weighted Subj.
YIELD	273.7	0.999	0.160
USE	27.0	0.619	0.037
CAPITAL COST	0.5	0.976	0.166
ANNUAL COST	0.1	0.111	0.013
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	8.0	0.778	0.109
ACCEPTANCE	1.0	0.000	0.000
DEPENDENCY	5.0	0.444	0.067

TOTAL SCORE = 0.662

Project = DESOMAN: A WATER RESOURCES RECHARGE/CONSERVATION SCHEME FOR OMAN

CAP ALL WELLS	0.662	CAP ALL PRIVATELY OWNED WELLS IN THE AREA
METER WELLS	0.657	INSTALL METERS ON ALL WELLS IN THE AREA
WELL INJECTION	0.646	DESIGN AN AQUIFER STORAGE AND RECOVERY PROGRAM
GREY WATER	0.600	DESIGN AND IMPLEMENT AN SEWAGE EFFLUENT REUSE PROGRAM
PERMIT WELLS	0.584	ISSUE FIVE YEAR CONSUMPTIVE USE PERMITS ON ALL WELLS
NO ACTION	0.414	DO NOT IMPLEMENT ANY POLICY FOR RECHARGE/CONSERVATION

Project = DSSOMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

FACTOR WEIGHTS

YIELD	0.170	QUANTITY OF WATER PRODUCED ANNUALY (in MGY) BY THE PLAN
CAPITAL COST	0.160	THE CAPITAL COST OF THE PLAN (in MILLION DOLLARS)
DEPENDENCY	0.150	THE DEPENDABILITY OF THE PLAN TO RECHARGE/CONSERVE WATER
FUTURE WORTH	0.140	THE FUTURE UTILITY (WORTH) OF THE PLAN (unitless)
ANNUAL COST	0.120	ANNUAL COST OF MAINTENANCE OF THE PLAN (in MILLION DOLLARS)
LIFETIME	0.110	THE EXPECTED LIFETIME (in YEARS) OF THE PLAN
ACCEPTANCE	0.090	THE ACCEPTABILITY OF THE PLAN BY THE PUBLIC (unitless)
USE	0.060	USE OF THE WATER FROM A CHOICE OF SEVEN (RATED) USES

Project = DSSOMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

FUNCTION FORMS

YIELD QUANTITY OF WATER PRODUCED ANNUALY (in MGY) BY THE PLAN
Objective : 0.1 273.7
Subjective : 0.000 1.000
Weight = 0.170

USE USE OF THE WATER FROM A CHOICE OF SEVEN (RATED) USES
Objective : 1.0 43.0
Subjective : 0.000 1.000
Weight = 0.060

CAPITAL COST THE CAPITAL COST OF THE PLAN (in MILLION DOLLARS)
Objective : 0.0 20.0
Subjective : 1.000 0.000
Weight = 0.160

ANNUAL COST ANNUAL COST OF MAINTENANCE OF THE PLAN (in MILLION DOLLARS)
Objective : 0.0 0.1
Subjective : 1.000 0.000
Weight = 0.120

LIFETIME THE EXPECTED LIFETIME (in YEARS) OF THE PLAN
Objective : 1.0 20.0
Subjective : 0.000 1.000
Weight = 0.110

FUTURE WORTH THE FUTURE UTILITY (WORTH) OF THE PLAN (unitless)
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.140

ACCEPTANCE THE ACCEPTABILITY OF THE PLAN BY THE PUBLIC (unitless)
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.090

DEPENDENCY THE DEPENDABILITY OF THE PLAN TO RECHARGE/CONSERVE WATER
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.150

Project = DSSCMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

NO ACTION: DO NOT IMPLEMENT ANY POLICY FOR RECHARGE/CONSERVATION

Factors	Objective	Subjective	Weighted Subj.
YIELD	27.4	0.100	0.017
USE	26.0	0.595	0.036
CAPITAL COST	0.0	1.000	0.160
ANNUAL COST	0.0	0.778	0.093
LIFETIME	5.0	0.211	0.023
FUTURE WORTH	1.0	0.000	0.000
ACCEPTANCE	9.0	0.889	0.080
DEPENDENCY	1.0	0.000	0.000

TOTAL SCORE = 0.409

Project = DSSOMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

PERMIT WELLS: ISSUE FIVE YEAR CONSUMPTIVE USE PERMITS ON ALL WELLS

Factors	Objective	Subjective	Weighted Subj.
YIELD	27.4	0.100	0.017
USE	10.0	0.214	0.013
CAPITAL COST	0.1	0.999	0.160
ANNUAL COST	0.0	0.978	0.117
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	5.0	0.444	0.062
ACCEPTANCE	6.0	0.556	0.050
DEPENDENCY	4.0	0.333	0.050

TOTAL SCORE = 0.579

Project = DSSOMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

GREY WATER: DESIGN AND IMPLEMENT AN SEWAGE EFFLUENT REUSE PROGRAM

Factors	Objective	Subjective	Weighted Subj.
YIELD	164.2	0.600	0.102
USE	28.0	0.595	0.036
CAPITAL COST	20.0	0.000	0.000
ANNUAL COST	0.1	0.000	0.000
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	10.0	1.000	0.140
ACCEPTANCE	8.0	0.778	0.070
DEPENDENCY	10.0	1.000	0.150

TOTAL SCORE = 0.608

Project = DSSOMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

WELL INJECTION: DESIGN AN AQUIFER STORAGE AND RECOVERY PROGRAM

Factors	Objective	Subjective	Weighted Subj.
YIELD	7.7	0.028	0.005
USE	17.0	0.381	0.023
CAPITAL COST	0.5	0.975	0.156
ANNUAL COST	0.1	0.522	0.063
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	6.0	0.556	0.078
ACCEPTANCE	10.0	1.000	0.090
DEPENDENCY	8.0	0.778	0.117

TOTAL SCORE = 0.641

Project = DSSOMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

METER WELLS: INSTALL METERS ON ALL WELLS IN THE AREA

Factors	Objective	Subjective	Weighted Subj.
YIELD	88.4	0.250	0.042
USE	18.0	0.405	0.024
CAPITAL COST	0.2	0.992	0.159
ANNUAL COST	0.0	0.611	0.073
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	9.0	0.889	0.124
ACCEPTANCE	3.0	0.222	0.020
DEPENDENCY	7.0	0.667	0.100

TOTAL SCORE = 0.653

Project = DSSOMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

CAP ALL WELLS: CAP ALL PRIVATELY OWNED WELLS IN THE AREA

Factors	Objective	Subjective	Weighted Subj.
YIELD	273.7	1.000	0.170
USE	27.0	0.619	0.037
CAPITAL COST	0.5	0.976	0.156
ANNUAL COST	0.1	0.111	0.013
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	8.0	0.778	0.109
ACCEPTANCE	1.0	0.000	0.000
DEPENDENCY	5.0	0.444	0.067

TOTAL SCORE = 0.662

Project = DSSCMAN2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

CAP ALL WELLS	0.662	CAP ALL PRIVATELY OWNED WELLS IN THE AREA
METER WELLS	0.653	INSTALL METERS ON ALL WELLS IN THE AREA
WELL INJECTION	0.641	DESIGN AN AQUIFER STORAGE AND RECOVERY PROGRAM
GREY WATER	0.608	DESIGN AND IMPLEMENT AN SEWAGE EFFLUENT REUSE PROGRAM
PERMIT WELLS	0.579	ISSUE FIVE YEAR CONSUMPTIVE USE PERMITS ON ALL WELLS
NO ACTION	0.409	DO NOT IMPLEMENT ANY POLICY FOR RECHARGE/CONSERVATION

Project = DSSOMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

FACTOR WEIGHTS

ANNUAL COST	0.170	ANNUAL COST OF MAINTENANCE OF THE PLAN (in MILLION DOLLARS)
YIELD	0.160	QUANTITY OF WATER PRODUCED ANNUALY (in MGY) BY THE PLAN
DEPENDENCY	0.150	THE DEPENDABILITY OF THE PLAN TO RECHARGE/CONSERVE WATER
FUTURE WORTH	0.140	THE FUTURE UTILITY (WORTH) OF THE PLAN (unitless)
CAPITAL COST	0.120	THE CAPITAL COST OF THE PLAN (in MILLION DOLLARS)
LIFETIME	0.110	THE EXPECTED LIFETIME (in YEARS) OF THE PLAN
ACCEPTANCE	0.090	THE ACCEPTABILITY OF THE PLAN BY THE PUBLIC (unitless)
USE	0.060	USE OF THE WATER FROM A CHOICE OF SEVEN (RATED) USES

Project = DSSOMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

FUNCTION FORMS

YIELD QUANTITY OF WATER PRODUCED ANNUALY (in MGY) BY THE PLAN
Objective : 0.1 273.7
Subjective : 0.000 1.000
Weight = 0.160

USE USE OF THE WATER FROM A CHOICE OF SEVEN (RATED) USES
Objective : 1.0 43.0
Subjective : 0.000 1.000
Weight = 0.060

CAPITAL COST THE CAPITAL COST OF THE PLAN (in MILLION DOLLARS)
Objective : 0.0 20.0
Subjective : 1.000 0.000
Weight = 0.120

ANNUAL COST ANNUAL COST OF MAINTENANCE OF THE PLAN (in MILLION DOLLARS)
Objective : 0.0 0.1
Subjective : 1.000 0.000
Weight = 0.170

LIFETIME THE EXPECTED LIFETIME (in YEARS) OF THE PLAN
Objective : 1.0 20.0
Subjective : 0.000 1.000
Weight = 0.110

FUTURE WORTH THE FUTURE UTILITY (WORTH) OF THE PLAN (unitless)
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.140

ACCEPTANCE THE ACCEPTABILITY OF THE PLAN BY THE PUBLIC (unitless)
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.090

DEPENDENCY THE DEPENDABILITY OF THE PLAN TO RECHARGE/CONSERVE WATER
Objective : 1.0 10.0
Subjective : 0.000 1.000
Weight = 0.150

Project = DSSOMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

PLAN EVALUATION

NO ACTION: DO NOT IMPLEMENT ANY POLICY FOR RECHARGE/CONSERVATION

Factors	Objective	Subjective	Weighted Subj.
YIELD	27.4	0.100	0.016
USE	26.0	0.595	0.036
CAPITAL COST	0.0	1.000	0.120
ANNUAL COST	0.0	0.778	0.132
LIFETIME	5.0	0.211	0.023
FUTURE WORTH	1.0	0.000	0.000
ACCEPTANCE	9.0	0.889	0.080
DEPENDENCY	1.0	0.000	0.000

TOTAL SCORE = 0.407

Project = DSSOMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

PLAN EVALUATION

PERMIT WELLS: ISSUE FIVE YEAR CONSUMPTIVE USE PERMITS ON ALL WELLS

Factors	Objective	Subjective	Weighted Subj.
YIELD	27.4	0.100	0.016
USE	10.0	0.214	0.013
CAPITAL COST	0.1	0.999	0.120
ANNUAL COST	0.0	0.978	0.166
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	5.0	0.444	0.062
ACCEPTANCE	6.0	0.556	0.050
DEPENDENCY	4.0	0.333	0.050

TOTAL SCORE = 0.587

Project = DSSCMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

PLAN EVALUATION

GREY WATER: DESIGN AND IMPLEMENT AN SEWAGE EFFLUENT REUSE PROGRAM

Factors	Objective	Subjective	Weighted Subj.
YIELD	164.2	0.600	0.096
USE	26.0	0.595	0.036
CAPITAL COST	20.0	0.000	0.000
ANNUAL COST	0.1	0.000	0.000
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	10.0	1.000	0.140
ACCEPTANCE	8.0	0.778	0.070
DEPENDENCY	10.0	1.000	0.150

TOTAL SCORE = 0.602

Project = DSSOMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

PLAN EVALUATION

CAP ALL WELLS: CAP ALL PRIVATELY OWNED WELLS IN THE AREA

Factors	Objective	Subjective	Weighted Subj.
YIELD	273.7	1.000	0.160
USE	27.0	0.619	0.037
CAPITAL COST	0.5	0.976	0.117
ANNUAL COST	0.1	0.111	0.019
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	8.0	0.778	0.109
ACCEPTANCE	1.0	0.000	0.000
DEPENDENCY	5.0	0.444	0.067

TOTAL SCORE = 0.619

Project = DSSCMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

PLAN EVALUATION

WELL INJECTION: DESIGN AN AQUIFER STORAGE AND RECOVERY PROGRAM

Factors	Objective	Subjective	Weighted Subj.
YIELD	7.7	0.028	0.004
USE	17.0	0.381	0.023
CAPITAL COST	0.5	0.975	0.117
ANNUAL COST	0.1	0.522	0.089
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	6.0	0.556	0.078
ACCEPTANCE	10.0	1.000	0.090
DEPENDENCY	8.0	0.778	0.117

TOTAL SCORE = 0.627

Project = DSSCMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

PLAN EVALUATION

METER WELLS: INSTALL METERS ON ALL WELLS IN THE AREA

Factors	Objective	Subjective	Weighted Subj.
YIELD	68.4	0.250	0.040
USE	18.0	0.405	0.024
CAPITAL COST	0.2	0.992	0.119
ANNUAL COST	0.0	0.611	0.104
LIFETIME	20.0	1.000	0.110
FUTURE WORTH	9.0	0.889	0.124
ACCEPTANCE	3.0	0.222	0.020
DEPENDENCY	7.0	0.667	0.100

TOTAL SCORE = 0.642

Project = OSSOMAN3: SENSITIVITY ANALYSIS FOR CAPITAL COST AND ANNUAL COST

METER WELLS	0.642	INSTALL METERS ON ALL WELLS IN THE AREA
WELL INJECTION	0.627	DESIGN AN AQUIFER STORAGE AND RECOVERY PROGRAM
CAP ALL WELLS	0.619	CAP ALL PRIVATELY OWNED WELLS IN THE AREA
GREY WATER	0.602	DESIGN AND IMPLEMENT AN SEWAGE EFFLUENT REUSE PROGRAM
PERMIT WELLS	0.587	ISSUE FIVE YEAR CONSUMPTIVE USE PERMITS ON ALL WELLS
NO ACTION	0.407	DO NOT IMPLEMENT ANY POLICY FOR RECHARGE/CONSERVATION

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

PLAN EVALUATION

WADI MAYH:

Factors	Objective	Subjective	Weighted Subj.
YIELD	1.4	0.145	0.012
CAPITAL COST	4.9	0.977	0.195
ANNUAL COST	191.0	0.972	0.243
QUALITY	250.0	0.833	0.058
DISTANCE	5.0	0.967	0.039
USE	10.0	1.000	0.020
LIFE TIME	20.0	0.500	0.075
IMPACT	2.0	0.889	0.027
DEPENDENCY	8.0	0.778	0.047
FUTURE WORTH	5.0	0.444	0.044

TOTAL SCORE = 0.760

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

PLAN EVALUATION

WADI KHAWD:

Factors	Objective	Subjective	Weighted Subj.
YIELD	2.9	0.289	0.023
CAPITAL COST	18.0	0.817	0.163
ANNUAL COST	90.0	0.992	0.248
QUALITY	250.0	0.833	0.058
DISTANCE	15.0	0.900	0.036
USE	10.0	1.000	0.020
LIFE TIME	20.0	0.500	0.075
IMPACT	3.0	0.778	0.023
DEPENDENCY	5.0	0.444	0.027
FUTURE WORTH	10.0	1.000	0.100

TOTAL SCORE = 0.774

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

WADI KHAWD	0.774
WADI MAYH	0.760
DESALINATION 3	0.551
DESALINATION 1	0.550
DESALINATION 2	0.533
WADI DAYQAH	0.477
BATINAH	0.337

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

FACTOR WEIGHTS

ANNUAL COST	0.250	The annual cost (O&M) of the project in thousand U.S.dollars
CAPITAL COST	0.200	The capital cost of the project in million U.S. dollars
LIFE TIME	0.150	The life time of the project in years
FUTURE WORTH	0.100	Adaptiveness to change in economy,technology and environment
YIELD	0.080	The quantity of water from source (base yield) in MGD
QUALITY	0.070	The quality of the water from source in mg/l chloride
DEPENDENCY	0.060	How vulnerable is the source to external forces
DISTANCE	0.040	Distance of the source from supply grid (km)
IMPACT	0.030	Impact of the project on culture,economy and research
USE	0.020	Irrigation(1),Domestic(2),Municipal(3),Industrial(4)

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

FUNCTION FORMS

YIELD The quantity of water from source (base yield) in MGD

Objective :	0.0	5.0	10.0
Subjective :	0.000	0.500	1.000

Weight = 0.080

CAPITAL COST The capital cost of the project in million U.S. dollars

Objective :	3.0	44.0	85.0
Subjective :	1.000	0.500	0.000

Weight = 0.200

ANNUAL COST The annual cost (O&M) of the project in thousand U.S.dollars

Objective :	50.0	2525.0	5000.0
Subjective :	1.000	0.500	0.000

Weight = 0.250

QUALITY The quality of the water from source in mg/l chloride

Objective :	200.0	350.0	500.0
Subjective :	1.000	0.500	0.000

Weight = 0.070

DISTANCE Distance of the source from supply grid (km)

Objective :	0.0	75.0	150.0
Subjective :	1.000	0.500	0.000

Weight = 0.040

USE Irrigation(1),Domestic(2),Municipal(3),Industrial(4)

Objective :	1.0	5.5	10.0
Subjective :	0.000	0.500	1.000

Weight = 0.020

LIFE TIME The life time of the project in years

Objective :	10.0	20.0	30.0
Subjective :	0.000	0.500	1.000

Weight = 0.150

IMPACT Impact of the project on culture.economy and research

Objective :	1.0	5.5	10.0
Subjective :	1.000	0.500	0.000

Weight = 0.030

DEPENDENCY How vulnerable is the source to external forces

Objective :	1.0	5.5	10.0
Subjective :	0.000	0.500	1.000

Weight = 0.060

FUTURE WORTH Adaptiveness to change in economy,technology and environment

Objective :	1.0	5.5	10.0
Subjective :	0.000	0.500	1.000

Weight = 0.100

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

PLAN EVALUATION

BATINAH:

Factors	Objective	Subjective	Weighted Subj.
YIELD	6.6	0.660	0.053
CAPITAL COST	67.2	0.217	0.043
ANNUAL COST	1798.0	0.647	0.162
QUALITY	250.0	0.833	0.058
DISTANCE	150.0	0.000	0.000
USE	9.0	0.889	0.018
LIFE TIME	10.0	0.000	0.000
IMPACT	9.0	0.111	0.003
DEPENDENCY	1.0	0.000	0.000
FUTURE WORTH	1.0	0.000	0.000

TOTAL SCORE = 0.337

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

PLAN EVALUATION

WADI DAYQAH:

Factors	Objective	Subjective	Weighted Subj.
YIELD	9.5	0.950	0.076
CAPITAL COST	83.0	0.024	0.005
ANNUAL COST	2430.0	0.519	0.130
QUALITY	250.0	0.833	0.058
DISTANCE	90.0	0.400	0.016
USE	10.0	1.000	0.020
LIFE TIME	15.0	0.250	0.037
IMPACT	1.0	1.000	0.030
DEPENDENCY	10.0	1.000	0.060
FUTURE WORTH	5.0	0.444	0.044

TOTAL SCORE = 0.477

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

PLAN EVALUATION

DESALINATION 2:

Factors	Objective	Subjective	Weighted Subj.
YIELD	5.0	0.496	0.040
CAPITAL COST	24.1	0.743	0.149
ANNUAL COST	4041.0	0.194	0.048
QUALITY	250.0	0.833	0.058
DISTANCE	1.0	0.993	0.040
USE	8.0	0.778	0.016
LIFE TIME	20.0	0.500	0.075
IMPACT	9.0	0.111	0.003
DEPENDENCY	5.0	0.444	0.027
FUTURE WORTH	8.0	0.778	0.078

TOTAL SCORE = 0.533

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

PLAN EVALUATION

DESALINATION 1:

Factors	Objective	Subjective	Weighted Subj.
YIELD	3.7	0.369	0.030
CAPITAL COST	21.6	0.773	0.155
ANNUAL COST	3085.0	0.387	0.097
QUALITY	250.0	0.833	0.058
DISTANCE	1.0	0.993	0.040
USE	8.0	0.778	0.016
LIFE TIME	15.0	0.250	0.037
IMPACT	8.0	0.222	0.007
DEPENDENCY	6.0	0.556	0.033
FUTURE WORTH	8.0	0.778	0.078

TOTAL SCORE = 0.550

Project = ALKHAWD: EVALUATION OF POTENTIAL WATER SUPPLY SOURCES FOR OMAN

PLAN EVALUATION

DESALINATION 3:

Factors	Objective	Subjective	Weighted Subj.
YIELD	6.3	0.630	0.050
CAPITAL COST	33.6	0.627	0.125
ANNUAL COST	4720.0	0.057	0.014
QUALITY	250.0	0.833	0.058
DISTANCE	1.0	0.993	0.040
USE	8.0	0.778	0.016
LIFE TIME	30.0	1.000	0.150
IMPACT	10.0	0.000	0.000
DEPENDENCY	4.0	0.333	0.020
FUTURE WORTH	8.0	0.778	0.078

TOTAL SCORE = 0.551

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

FACTOR WEIGHTS

ANNUAL COST	0.250	The annual cost (O&M) of the project in thousand U.S.dollars
YIELD	0.200	The quantity of water from source (base yield) in MGD
LIFE TIME	0.150	The life time of the project in years
FUTURE WORTH	0.100	Adaptiveness to change in economy,technology and environment
CAPITAL COST	0.080	The capital cost of the project in million U.S. dollars
QUALITY	0.070	The quality of the water from source in mg/l chloride
DEPENDENCY	0.060	How vulnerable is the source to external forces
DISTANCE	0.040	Distance of the source from supply grid (km)
IMPACT	0.030	Impact of the project on culture,economy and research
USE	0.020	Irrigation(1),Domestic(2),Municipal(3),Industrial(4)

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

FUNCTION FORMS

YIELD The quantity of water from source (base yield) in MGD

Objective :	0.0	5.0	10.0	
Subjective :	0.000	0.500	1.000	
				Weight = 0.200

CAPITAL COST The capital cost of the project in million U.S. dollars

Objective :	3.0	44.0	85.0	
Subjective :	1.000	0.500	0.000	
				Weight = 0.080

ANNUAL COST The annual cost (O&M) of the project in thousand U.S.dollars

Objective :	50.0	2525.0	5000.0	
Subjective :	1.000	0.500	0.000	
				Weight = 0.250

QUALITY The quality of the water from source in mg/l chloride

Objective :	200.0	350.0	500.0	
Subjective :	1.000	0.500	0.000	
				Weight = 0.070

DISTANCE Distance of the source from supply grid (km)

Objective :	0.0	75.0	150.0	
Subjective :	1.000	0.500	0.000	
				Weight = 0.040

USE Irrigation(1),Domestic(2),Municipal(3),Industrial(4)

Objective :	1.0	5.5	10.0	
Subjective :	0.000	0.500	1.000	
				Weight = 0.020

LIFE TIME The life time of the project in years

Objective :	10.0	20.0	30.0	
Subjective :	0.000	0.500	1.000	
				Weight = 0.150

IMPACT Impact of the project on culture,economy and research

Objective :	1.0	5.5	10.0	
Subjective :	1.000	0.500	0.000	
				Weight = 0.030

DEPENDENCY How vulnerable is the source to external forces

Objective :	1.0	10.0		
Subjective :	0.000	1.000		
				Weight = 0.060

FUTURE WORTH Adaptiveness to change in economy,technology and environment

Objective :	1.0	5.5	10.0	
Subjective :	0.000	0.500	1.000	
				Weight = 0.100

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

BATINAH:

Factors	Objective	Subjective	Weighted Subj.
YIELD	6.6	0.660	0.132
CAPITAL COST	67.2	0.217	0.017
ANNUAL COST	1798.0	0.647	0.162
QUALITY	250.0	0.833	0.058
DISTANCE	150.0	0.000	0.000
USE	9.0	0.889	0.018
LIFE TIME	10.0	0.000	0.000
IMPACT	9.0	0.111	0.003
DEPENDENCY	1.0	0.000	0.000
FUTURE WORTH	1.0	0.000	0.000

TOTAL SCORE = 0.391

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

DESALINATION 1:

Factors	Objective	Subjective	Weighted Subj.
YIELD	3.7	0.369	0.074
CAPITAL COST	21.6	0.773	0.062
ANNUAL COST	3085.0	0.387	0.097
QUALITY	250.0	0.833	0.058
DISTANCE	1.0	0.993	0.040
USE	8.0	0.778	0.016
LIFE TIME	15.0	0.250	0.037
IMPACT	4.0	0.667	0.020
DEPENDENCY	5.0	0.444	0.027
FUTURE WORTH	8.0	0.778	0.078

TOTAL SCORE = 0.508

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

DESALINATION 2:

Factors	Objective	Subjective	Weighted Subj.
YIELD	5.0	0.496	0.099
CAPITAL COST	24.1	0.743	0.059
ANNUAL COST	4041.0	0.194	0.048
QUALITY	250.0	0.833	0.058
DISTANCE	1.0	0.993	0.040
USE	8.0	0.778	0.016
LIFE TIME	20.0	0.500	0.075
IMPACT	5.0	0.556	0.017
DEPENDENCY	4.0	0.333	0.020
FUTURE WORTH	8.0	0.778	0.078

TOTAL SCORE = 0.510

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

DESALINATION 3:

Factors	Objective	Subjective	Weighted Subj.
YIELD	6.3	0.630	0.126
CAPITAL COST	33.6	0.627	0.050
ANNUAL COST	4720.0	0.057	0.014
QUALITY	250.0	0.833	0.058
DISTANCE	1.0	0.993	0.040
USE	8.0	0.778	0.016
LIFE TIME	30.0	1.000	0.150
IMPACT	6.0	0.444	0.013
DEPENDENCY	3.0	0.222	0.013
FUTURE WORTH	8.0	0.778	0.078

TOTAL SCORE = 0.558

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

WADI DAYQAH:

Factors	Objective	Subjective	Weighted Subj.
YIELD	9.5	0.950	0.190
CAPITAL COST	83.0	0.024	0.002
ANNUAL COST	2430.0	0.519	0.130
QUALITY	250.0	0.833	0.058
DISTANCE	90.0	0.400	0.016
USE	10.0	1.000	0.020
LIFE TIME	15.0	0.250	0.037
IMPACT	1.0	1.000	0.030
DEPENDENCY	10.0	1.000	0.060
FUTURE WORTH	5.0	0.444	0.044

TOTAL SCORE = 0.588

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

WADI MAYH:

Factors	Objective	Subjective	Weighted Subj.
YIELD	1.4	0.145	0.029
CAPITAL COST	4.9	0.977	0.078
ANNUAL COST	191.0	0.972	0.243
QUALITY	250.0	0.833	0.058
DISTANCE	5.0	0.967	0.039
USE	10.0	1.000	0.020
LIFE TIME	20.0	0.500	0.075
IMPACT	2.0	0.889	0.027
DEPENDENCY	3.0	0.222	0.013
FUTURE WORTH	5.0	0.444	0.044

TOTAL SCORE = 0.626

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

PLAN EVALUATION

WADI KHAWD:

Factors	Objective	Subjective	Weighted Subj.
YIELD	2.9	0.289	0.058
CAPITAL COST	18.0	0.817	0.065
ANNUAL COST	90.0	0.992	0.248
QUALITY	250.0	0.833	0.058
DISTANCE	15.0	0.900	0.036
USE	10.0	1.000	0.020
LIFE TIME	20.0	0.500	0.075
IMPACT	3.0	0.778	0.023
DEPENDENCY	3.0	0.222	0.013
FUTURE WORTH	10.0	1.000	0.100

TOTAL SCORE = 0.697

Project = ALKHAWD2: SENSITIVITY ANALYSIS FOR CAPITAL COST AND YIELD

WADI KHAWD	0.697
WADI MAYH	0.626
WADI DAYQAH	0.588
DESALINATION 3	0.558
DESALINATION 2	0.510
DESALINATION 1	0.508
BATINAH	0.391

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Hussam will be employed by the Ministry of Water Resources in the Sultanate of Oman where he will reside with his family.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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